5-2010

Kinetics at front foot contact of cricket bowling during a 10-over spell

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KINETICS AT FRONT FOOT CONTACT OF CRICKET

BOWLING DURING A 10-OVER BOWLING SPELL

by

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Bachelor of Science
University of Pretoria, South Africa
2006

Honors of Science
University of Pretoria, South Africa
2007

A thesis submitted in partial fulfillment
of the requirements for the

Masters of Science Degree in Kinesiology
Department of Kinesiology and Nutrition Sciences
School of Allied Health Sciences
Division of Health Sciences

Graduate College
University of Nevada, Las Vegas
May 2010

THE GRADUATE COLLEGE

We recommend the thesis prepared under our supervision by

Jacobus Noel Liebenberg

entitled

Kinetics at Front Foot Contact of Cricket Bowling during a 10-over Spell

be accepted in partial fulfillment of the requirements for the degree of

Masters of Science in Kinesiology

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May 2010

ABSTRACT

Kinetics at Front Foot Contact of Cricket Cowling during a 10-over spell

by

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The purpose of this study was to determine what effect bowling a 10 over spell (60 balls) would have on approach velocity, vertical ground reaction forces and shock attenuation during the front foot contact of a delivery stride in cricket.

Ten Amateur cricket players (age 27±4 years, height 1.78±0.3 m, mass 80.6±8.5 kg) participated in the study. Testing was conducted at University of Nevada, Las Vegas in the Biomechanics laboratory. Participants performed a 10-over bowling spell from a 12 meter run-up. These dependent variables were measured and calculated during the bowling protocol: 1) approach velocity 2) vertical ground reaction force (vGRF) and 3) shock attenuation (SA). A 15 min self-directed warm-up was performed prior to starting the 10-over bowling spell. After the warm-up was completed subjects were instrumented with two uni-axial accelerometers (PCB Piezotronics, model #352C68-6 and #352C68) to obtain acceleration data (1000Hz) and ultimately calculating shock attenuation. One accelerometer was placed on the distal anterior-medial aspect of the tibia and the second accelerometer was placed on the forehead along the midline of the body. Participants were then asked to bowl a 10 over bowling spell with 8 min breaks between. During the delivery stride participants had to strike the force platform with their front foot.

Accelerometer and vertical ground reaction force data were collected for the time total time that the front foot was in contact with the ground. A force platform (Kistler, 9281C, SN-616902) was used to collect vertical ground reaction force data (1000Hz).

Dependent variables namely approach velocity, vertical ground reaction force and shock attenuation was analyzed using one way repeated measures ANOVAs with planned comparison tests to determine where differences occurred across the 10 overs. Overs were combined into beginning (overs 1&2), middle (overs 5&6) and end (overs 9&10). SA was calculated by the following equation: SA = (1- Head/Leg)*100.

A significant change across the 10-over bowling spell were found for approach velocity ($p<0.001$), vertical ground reaction force ($p<0.024$) and shock attenuation ($p<0.032$). Planned comparison tests identified a significant difference ($p<0.05$) for APV between the beginning (4.34 ± 1.22 m/s) and middle (5.18 ± 1.42 m/s) as well as a significant difference between middle (5.18 ± 1.42) and end (4.13 ± 1.27 m/s). The vGRF results illustrated a significant difference ($p<0.05$) between the middle (4.09 ± 0.81 BW) and the end (3.76 ± 0.58 BW). No significant difference ($p<0.05$) was found in vGRF between the beginning (4.03 ± 0.69) and the middle (4.09 ± 0.81BW). An overall significant difference was found in SA across all 10 overs. A significant difference was found between the middle (79.48 ± 10.43%) and the end (78.23 ± 10.72%) as well as between beginning and end.

High vGRF values have has been reported in front foot contact during cricket bowling in fast/medium bowlers which might play a role in overuse injuries experienced by bowlers. This study provided groundwork in understanding how these forces change over a 10-over bowling spell and how these forces maybe attenuated during front foot

contact. It was concluded that there was a definite change observed across the 10 overs in the magnitude of vGRF produced and how these forces are attenuated. This study suggests that coaches and fitness specialists should pay careful attention to these changes relative to overuse injuries potential.

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ACKNOWLEDGEMENTS

I would like express my gratitude to all the people who made this experience a reality for me. Firstly, I would like thank the Father above for the Grace and Power he provided me with during this journey to make my dream a reality. Without Him nothing would be possible. I would like to pay special thanks to my father and the Sapsford family for their support and believe in me to overcome all the obstacles to achieve my Masters Degree. I would like to thank all of the faculty members at the University of Nevada, Las Vegas and at the University of Pretoria, South Africa for the time and effort they invested in me to peruse my degree. Thank you to all my friends and fellow graduate students for assisting me in the everyday life of a grad student. I would like to thank Dr. John Mercer in his ability to teach me about the technical and research aspects of biomechanics through his excellent knowledge of the field.

I would like to pay special thanks to a few specific people. A great appreciation to Dr. Darleen Kluka, Dr. Gosslin and Dr. Salmar Burger for making this degree possible through their perseverance and believe in me. A special thanks to the Smith, Santoro, Baker, Parveen, Stanford and Central families for their friendship, which made my two years a great experience. A special appreciation for my dear friend Philana-Lee Gouws for her continuous support and teamwork in making our time in the US a success.

Last but not least, I can't describe the appreciation and thanks to my mentor and chair Dr. Janet Dufek for her unbelievable support, guidance and patience. She made me believe in myself and always picked me up during tough times. Her tremendous work ethic and ability to have a positive impact on me will stay with me the rest of my live. "Keep your head up and pay attention to detail" – J.S Dufek.

CHAPTER 1

INTRODUCTION

Cricket is one of the world's major team sports involving two teams of eleven players each. Although the game play and rules are very different than baseball, the basic concept between the two sports still stays the same. A batsmen stands on side of the pitch and the bowler bowls the ball to the batsmen from the other side of the pitch (Figure1).

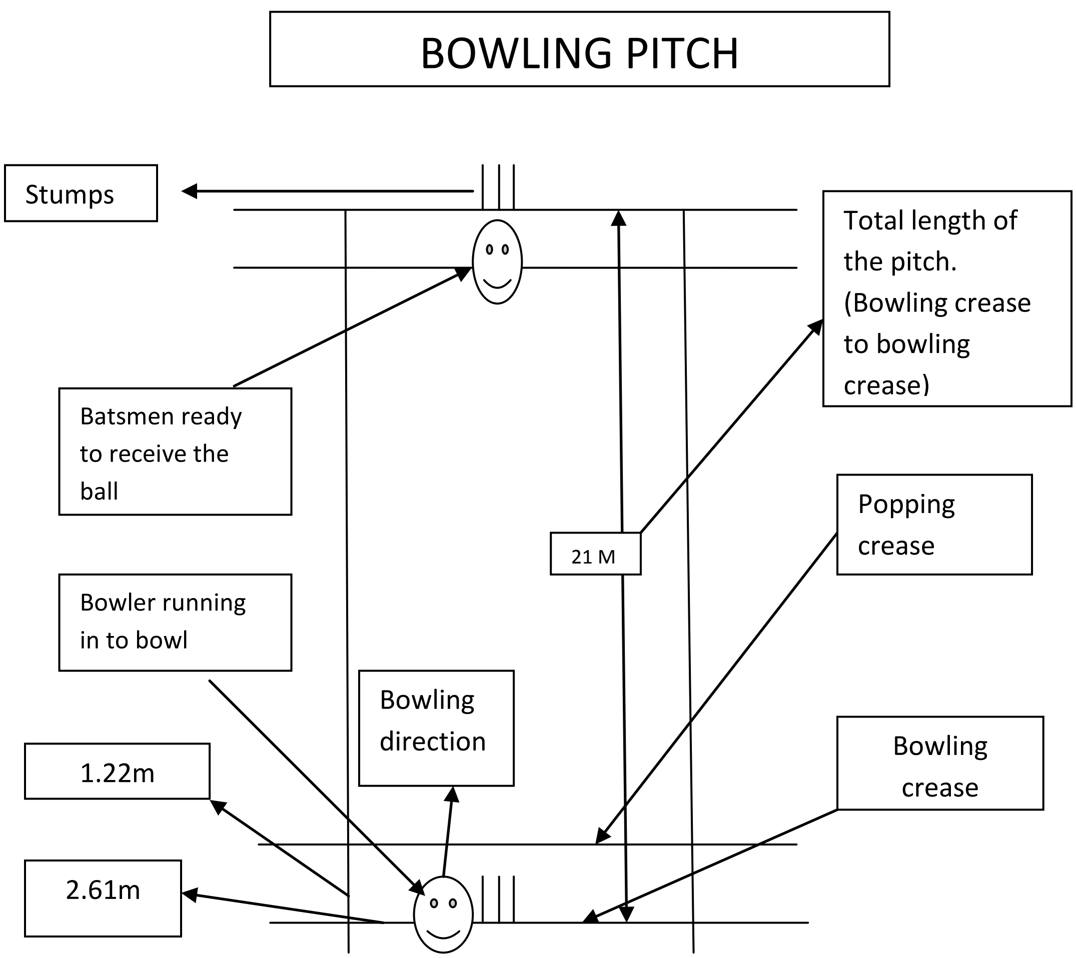

Figure 1: Illustration of the main dimensions of a cricket pitch as well as the orientation and direction of the bowler and batsmen.

The batsman tries to hit the ball into the outfield to accumulate runs. Teams bat in successive innings and attempt to score runs, while the opposing team bowls (with fast and spin bowlers) and attempt to bring an end to the batting team's innings. After each team has batted an equal number of innings (either one or two, depending on the type of match), the team with the most runs wins. Today, elite players are expected to train longer, harder and earlier in life to excel in their chosen sport, and modern cricket is no exception. The demands placed on a cricketer have increased because of the repetitive nature of the game, often for long periods of time, which leads to common overuse injuries, particularly in fast/medium bowlers (Orchard et al., 2006).

A bowling injury is defined as physical damage that prevents the completion of a practice session or cricket match and the prevention of being able to be selected for a team (Elliot et al., 2009). Gregory et al. (2004) reported that 49% of South African first-league and provincial cricketers reported a seasonal injury (September – April), 42% of these injuries being chronic injuries and 7% being acute injuries. In England 45% of acute cricket injuries occurred to the lower limb and injuries were higher in bowlers compared to batsmen and fielders. Young bowlers (age 16-20) who bowl in more than 17 matches per year have a higher prevalence (58%) of overuse injuries in the lower limbs compared to any other bowlers (38%) (Foster et al., 1989). In a study done by Gregory et al. (2004), injuries that lead to pain, impairment or preventing bowling performance most commonly affect the following anatomical sites: knee, ankle and low back. All of the injuries found at the knee were due to overuse problems. Examples of overuse injuries are: patellofemoral pain syndrome, tibial stress syndrome, tibial stress fracture, and Achilles tendonitis.

Guidelines were established by the English and Welsh cricket boards on what would be a good number off balls to be bowled in training and matches to help prevent overuse injuries in cricket bowlers (Gregory, et al., 2004); (Table 1). This guideline emphasizes the importance of reducing overuse injuries and the effect that prolonged bowling can have on cricket bowlers.

Table 1- Directives on fast bowling from England and Wales Cricket Board

Age (yrs)	Matches	Practices	Maximum of matches & practices in 1 week
Under 13	2 spells of 3-4 overs	2 p/w; 30 b/s	3
Under 15	2 spells of 4-5 overs	2 p/w; 36 b/s	3
Under 17	3 spells of 4-5 overs	3 p/w; 36 b/s	4
Under 19	3 spells of 5-6 overs	3 p/w; 42 b/s	4
Senior	3 spells of 6-8 overs	3 p/w; 48 b/s	n/a

NOTE: p/w = per week and b/w = balls/sessions

There are several components that contribute to the occurrence of overuse injuries. These components continuously interact with each other. Messier et al. (1991) divided these components into extrinsic and intrinsic factors. Extrinsic factors are those which come from the external environment. In cricket, such examples are bowling surfaces or bad weather conditions. Intrinsic factors are internal components of the body, such as movement of a limb or the contraction of a muscle. Overuse injuries in cricket can possibly occur when these internal components are placed under continuous stress or repetitive movement causing acute or overuse injuries.

Two intrinsic factors related to possible causes of overuse injuries are vertical ground reaction force (vGRF) and shock attenuation (SA) (Derrick et al., 1998). vGRF is seen as a shock wave that is transmitted through the skeletal system when the foot makes contact to the ground. SA is when the amplitude of the shock wave is reducing by absorbing impact energy produced by the ground (Mercer et al., 2003). Extensive research has been done of what kind of vGRF are produced during fast/medium bowlers in cricket and several researchers has suggested that vGRF may play a role in overuse injuries in cricket bowlers (Stuelcken et al., 2007; Hurrion et al., 2000; Fitch, 1989).

Although SA is still seen as a concept and we do not know how the body absorbs this shock, it will be beneficial to cricket to try and determine how much of this impact energy is absorbed during bowling a 10 over spell.

Purpose of the Study

The purpose of this study was to determine what effect bowling a 10 over spell (60 balls) would have on approach velocity, vertical ground reaction forces and shock attenuation during the front foot contact of a delivery stride in cricket.

Research Hypothesis

Research Hypothesis 1: vGRF will not stay constant over a 10 over bowling spell.

Null Hypothesis 1: vGRF will remain constant over a 10 over bowling spell.

Research Hypothesis 2: SA will not remain constant over a 10 over bowling spell.

Null Hypothesis 2: SA will stay constant over a 10 over bowling spell.

Research Hypothesis 3: APV will not remain constant over a 10 over bowling spell.

Null Hypothesis 3: APV will stay constant over a 10 over bowling spell.

Definitions of Terms

Acceleration: Time rate of change in velocity

Front foot contact (FFC): When the front foot of the bowler makes contact with the ground during the delivery stride.

Ground reaction force (GRF): An equal and opposite force that is exerted back against the body by the ground when a person's foot strikes the ground.

Head Peak impact acceleration (a_{head}): The peak impact acceleration recorded by an accelerometer mounted on the forehead immediately following foot contact.

Leg Peak impact acceleration (a_{leg}): The peak impact acceleration recorded by an accelerometer mounted on the medial aspect of the distal tibia immediately following foot contact.

Overuse injuries: Injuries occurring when the musculoskeletal system receives stress over a period of time, causing fatigue beyond the tolerances of a specific structure.

Shock attenuation (SA): The process of attenuating shock and therefore reducing the impact magnitude between segments of the body. Operationally, it is the measure of peak impact reduction of leg acceleration and head acceleration. The formula to calculate is:

$$SA = \left(1 - \frac{\text{Head Impact Acceleration}}{\text{Leg Impact Acceleration}} \right) \times 100$$

<u>Shock Wave:</u> Initiated by the foot-ground contact which travels through the musculoskeletal system up to the head.

<u>Vertical ground reaction force</u> (vGRF): The vertical component of the ground reaction force vector.

<u>Assumptions</u>

1. It was assumed that all instructions were given to the subjects in a proper and sufficient way and that the subjects followed instructions in the correct manner.
2. It was assumed that bowlers experienced possible general tiredness in the latter overs of the 10 over bowling spell.

<u>Limitations</u>

1. The results can only be inferred to medium speed bowlers and not fast or slow speed bowlers.
2. Bowlers may possibly not perform a maximal bowling effort due to the laboratory environment and instrumentation.
3. The indoor bowling surface used was different compared to outdoor bowling surfaces and could have possibly affected the results. Results can still be inferred to outdoor bowling conditions (Hurrion et al., 1997).
4. Each bowler wore a different type and model shoe which may have had an influence in the way each shoe absorbs vGRF, ultimately resulting in different amount of impact energy the body had to absorb.

CHAPTER 2

REVIEW OF THE LITERATURE

Fast/medium bowling in cricket is an activity which produces high ball velocities at release through generating a variety of forces and torques in the body to accomplish these ball velocities at delivery. Bowlers undergo a huge amount of twisting, bending, rotation, flexion and extension over a short period with the added necessity of accommodating the ground reaction forces generated (McGrath et al., 1996). It is the high speed and force at which these actions are performed that increase the possibility for a fast/medium to occur injuries (McGrath et al., 1996). During the delivery stride one of the most important movements performed is when the bowler puts the front foot down very hard on the pitch, which is referred to as “front foot contact” (FFC) (Hurrion, et al., 2000). When the front foot contacts the ground during delivery stride (FFC), high magnitudes of impact forces are created that act on the body and consequently the body has to attenuate these forces and absorb the impact energy in such a way to eliminate any possible injury (Hurrion et al., 2000). The forces acting on the body can be better explained with the help of Newton’s third law of motion: for every action there is an equal and opposite reaction. This law is applied when a bowler’s front foot strikes the ground during the delivery stride, in which an equal and opposite force is applied by the ground which is referred to as the ground reaction force (GRF).

Although the vertical component of the GRF (vGRF) illustrates the force that the body has to attenuate during impact, it is still important to know that the body also has to accommodate the anterior-posterior (a-p) and medial lateral forces (m-l) during foot contact

Nordin & Frankel (2001) suggest that shock attenuation is the term that refers to the body attenuating forces through rigid structures (e.g., vertebral column, bones, cartilage and joints) as well as soft tissue structures (e.g., muscles, ligaments and tendons). The vGRF is directly related to the amount of shock the body has to attenuate and absorb, therefore the higher the vGRF the higher the amount of shock the body has to absorb. Hurrion et al. (2000) reported that peak vGRF at FFC for fast bowlers range between 2.08-9.51 BW with mean of 5.75 BW. The mean peak impact vGRF occurs 16 milliseconds after the front foot contact on the pitch, compared to a mean peak impact (F1) time of 30 milliseconds in running (Hurrion et al., 2000). The vGRF experienced by fast/medium bowlers is greater than the average vGRF acting on a marathon runner (Munro et al., 1987). The body has the ability to tolerate these forces during the delivery stride, although this ability seems to decrease over time because of the repetitive action during the game, which might lead to an increased possibility of injury (Fitch, 1989). Hurrion et al. (2000) supported the same idea showing that large impact forces at front foot contact produce biomechanical stresses on the body which are likely to cause overuse injuries. A number of studies have investigated the characteristics of vGRF during fast/medium bowling in cricket (Stuelcken et al., 2007; Hurrion et al., 2000; Elliot & Foster, 1984; & Mason et al., 1989), but none of these studies investigated the shock attenuation of front foot contact during the delivery. Shock attenuation is the process of reducing impact energy between the foot and head (Mercer et al., 2003). Due to the high volume of bowling deliveries being bowled in a given season, certain body structures are placed under repeated stress when continuously absorbing impact forces between 3-8 times body weights (BW).

Also, MacLaren et al. (1989) suggest that these anatomical structures are placed under greater stress if the muscles become fatigued during running long or repeated distances. We can therefore hypothesize that repeated front foot contact (FFC) during a season of bowling where the body has to absorb vGRFs up 3-5 times that of running can lead to possible overuse injuries. Cricket is an outdoor sport. Hurrion et al. (2000) reported no significant difference in vGRF when comparing outdoor vs. indoor testing conditions. Similar vGRF values were found during indoor testing despite limitations in space and the bowlers not having the ability to take a full run-up. Taylor et al. (2000) suggested that further research on the capability of different shoe materials to absorb high impact forces during prolonged bowling of fast/medium bowlers as well as the body's ability to absorb these impact forces during FFC will be very beneficial to the world of cricket. Nordin and Franklin (2001) established a model (Figure 2) which illustrates two possible paths that can lead to bone injury due to fatigued muscles: 1) the loss of shock-absorbing capacity of muscles or 2) a change in the movement pattern to compensate for the change in muscle ability.

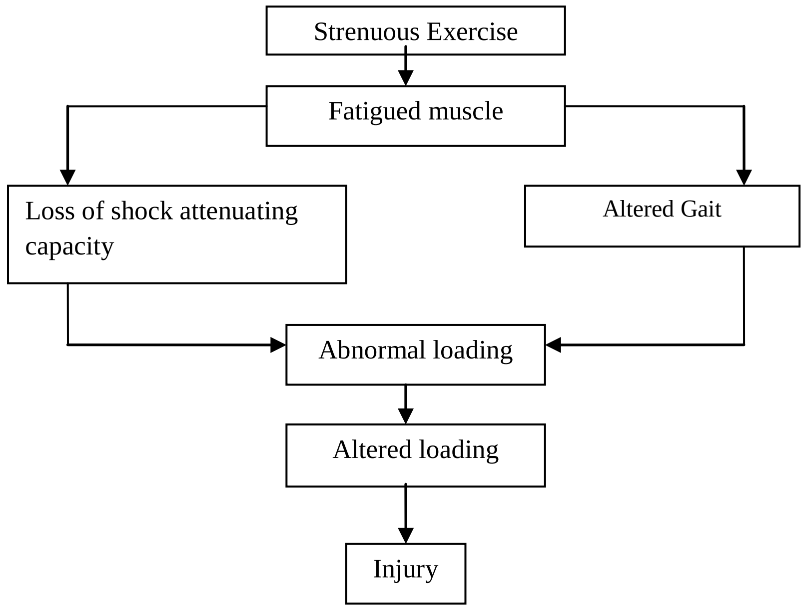

Figure 2: Injury model. Reproduced from "Basic Biomechanics of the Musculoskeletal System" Nordin, M & Franklin, V.H., 2001, P 4

Modifications to this model for application to cricket bowling are given in Figure 3. It is valid to make such modification because gait is the action performed during running, but the action performed during cricket bowling is gait and the bowling action, both of which can be influenced by fatigued muscles or some form of fatigue after strenuous exercise. This study will focus on the path that illustrates the loss of shock attenuation capability that ultimately may lead to injuries, (bold in Figure 3) as well as try to establish if a fast/medium bowler looses the ability to absorb shock over a period of a 10 over spell. Alternatively does a fast/medium bowler attenuate the same shock over a 10 over spell by altering his bowling action?

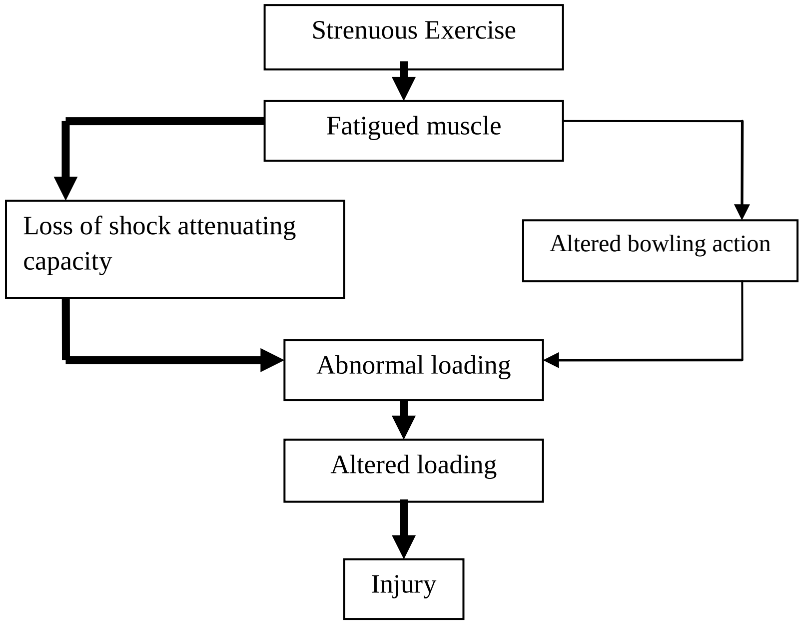

Figure 3: Injury model for application to fast/medium cricket bowlers. Adapted from "Basic Biomechanics of the Musculoskeletal System" Nordin, M & Franklin, V.H., 2001, P 41

Biomechanics of the Bowling Delivery

A bowling delivery consists of 4 main phases: 1) run-up to back foot contact, 2) pre-delivery, 3) delivery stride and 4) follow through (McGrath et al., 1996).

In the first phase each bowler slowly starts walking or jogging, building up his speed to the point where he leaps into the air to start the pre-delivery stride over a specific measured run-up distance (Bartlett et al., 1995). Each bowler chooses a self selected run-up length, which varies from 10-30 meters for a fast/medium bowler (Davis, & Blanksby, 1976b). The bowler starts the run-up with the purpose to reach as high as possible horizontal velocity 3-4 strides before the bowling crease (Elliot et al., 1986). The approach velocity of the bowler influences the release velocity of the ball (Stockhill, & Bartlett, 1993).

The higher the velocity at back foot impact, the greater the influence on the alignment of the hips and shoulder during the delivery stride (Burnett et al., 1998). The second phase, known as the pre-delivery phase starts when a right handed bowler pushes off on his left foot to leap into the air and it ends when the back foot strikes the ground after the leap is completed (Melbourne Cricket Council, 1976; Bartlett et al., 1995). During this stride when the bowler is in flight, the right foot passes in front of the left foot landing and contacts the ground parallel with the bowling crease (Bartlett et al., 1995). The pre-delivery stride is also when the bowler changes the position of his shoulders from a normal running position to a position where the shoulders are pointing down the pitch, perpendicular to the bowling crease (Bartlett et al., 1995). The delivery stride is the third and most important phase due to a combination of forces acting on the body, which increases the possibility of overuse or acute injuries making it the most important area of research for cricket scientists (Mason et al., 1989; Foster et al., 1989; Bartlett et al., 1995). The follow through is the last of the four main phases of a bowling delivery. This area has not received much attention due to most analyses being stopped after the ball has been delivered (Bartlett et al., 1995).

During the follow through the right arm should pass the left thigh as close as possible (Elliot and Foster, 1989). Elliot et al. (1989) also suggested that the bowler should gradually reduce his speed until the point of being stationary.

The delivery stride can be divided into eight important subdivisions: 1) action classification, 2) back foot strike, 3) front foot strike, 4) stride length and alignment, 5) front knee angle, 6) shoulder and hip orientation, 7) non-bowling arm and trunk

movements as well as 8) the ball release (Bartlett et al., 1995). Each of the subdivisions of the delivery stride is next discussed in more detail.

Action Classification

Bowlers can be classified into one of two types of bowling action, an open action or a side on action (Elliot, & Foster, 1984). The two predictors used to classify bowlers between the two actions include 1) the angle at which the back foot makes contact with the ground at the end of the pre-delivery stride, and 2) the alignment of the shoulders at the beginning of the delivery stride (Foster et al., 1989). If the back foot lands parallel (270 degrees) to the bowling crease and the shoulders align perpendicular (180 degrees) to the bowling crease, it can be considered as the ideal side on action (Elliot, & Foster, 1984; Melbourne Cricket Council, 1976; Bartlett et al., 1995). When the shoulder alignment is greater than 200 deg and the back foot is placed at an angle of more than 270 degrees it is considered to be an open action (Elliot, & Foster, 1984; Melbourne Cricket Council, 1976; & Bartlett et al., 1995). Elliot and Foster (1984) reported that a number of bowlers combine the types of bowling actions to form a mixed action; also suggesting that it is difficult to categorize a bowler completely to one action type.

Back Foot Contact

At the start of the delivery stride most weight is placed on the back foot. Trunk flexion occurs at the same time the back foot makes contact with the ground and it is closely related to the position at which the back foot is placed (Bartlett, & Best, 1998).

When the back foot is placed parallel to the ground, lateral flexion of the spine is more prominent making the amount of leaning backward greater compared with an open action (Bartlett et al., 1995). Penrose et al. (1976) reported that the restricted hyper

extension of the back leads to the smaller degree of trunk flexion. Back foot contact provides lesser vGRF values than front foot contact (Hurrion et al., 2000).

Front Foot Contact

This is the end phase of the delivery stride. The most prominent aspect of this phase is the magnitude of the GRFs that act on the body due to the foot being placed on the ground with a high amount of force (Bartlett, & Best, 1998). Factors that affect the magnitude of reaction forces acting on the body at front foot contact include: 1) approach velocity, and 2) front knee angle (Bartlett et al., 1995). Research has shown no significant differences among peak vGRF, different bowling techniques and any kinematic parameters studied (Saunders, & Coleman, 1991; Elliot, & Foster, 1984; & Elliot et al., 1992).

Stride Length and Alignment

Stride length is the distance between the back foot strike and front foot contact of the delivery stride (Bartlett et al., 1995). Elliot et al. (1986) recommended that the stride length should be measured relative to standing height when comparing different studies and variables such as age and gender. Relative mean values of stride length ranging from 70-86% (juniors) and 86% (seniors) have been reported (Elliot et al., 1986; Elliot et al., 1992; Stockhill, 1994). Elliot et al. (1992) established a range for an adult bowling stride length of 75-85% of stature.

The length of a bowler's stride length is dependent on the approach velocity of the bowler (Melbourne Cricket Council, 1997; Elliot et al., 1986). The slower the approach speed of the bowler the smaller the stride length and the faster the approach speed the greater the stride length (Elliot, & Foster, 1984). Elliot and Foster (1984)

reported values of 1.34 m for an approach velocity of 3.8 m/s and 1.67 m for an approach velocity of 4.6 m/s.

The next area of interest in the delivery stride is the alignment of the back and front foot. It is recommended that the back foot, front foot and the wickets at the batsmen's end should form a straight line (Elliot et al., 1986). A range of average displacements for the front foot relative to the back foot varied from 3.2 cm to the off-side (Elliot et al., 1986) to 10.9 cm to the on-side (Elliot et al., 1992). Any displacement to the off-side suggests a more front-on action and any displacement to the on-side illustrates a more side-on action (Elliot et al., 1992; Elliot, & Foster, 1984). In the more recent study that Elliot et al. (1992) conducted, contradicting results where compared to the study that they conducted in 1984. The results showed only 20% of the bowlers who had an average displacement of 10.9 cm to the on-side were side-on bowlers. Limited research has been conducted to establish the direction of front foot placement during the delivery stride (Bartlett et al., 1995).

Front Knee Angle

The front knee actions can be categorized into three primary actions (Bartlett et al., 1995). The first type illustrates when the front leg is fully extended or close to being fully extended at the time of ball release. Elliot et al. (1986) suggested that a straight leg action assists in reaching a higher ball release speed because the straight leg action produces a stable lower body, providing the bowler with an effective lever (Elliot et al., 1986). Any knee angle greater than 150 degrees would be classified as a straight leg action (Elliot et al., 1986) which will provide the above mentioned advantages. The second type of action is when the bowler lands with a flexed knee failing to fully extend

at any time after front foot contact (Bartlett et al., 1995). A knee angle less than 150 degrees are considered to be a flexed knee action (Bartlett et al., 1995). The last type of knee action is a slightly bent knee at front foot impact progressively turning into a straight leg action at ball release (Bartlett et al., 1995). This action provides the benefits of a straight leg action but also has a suggested advantage of attenuating forces better due to the slightly bent knee at front foot contact (Elliot et al., 1986; Bartlett et al., 1995).

Shoulder Orientation

The orientation of the shoulders during the delivery stride will highly depend on the type of action used by the bowler (side-on, mixed or front-on). During the push off in the pre-delivery stride going into flight phase, the shoulders start to rotate toward the batsmen (Curtin et al., 1974). The rotation toward the batsmen continues during the flight phase, ultimately lining up in a straight line with the batsman at 0 degrees. Counter rotation begins when the hips of the bowler start to rotate in the direction of the batsman (Bartlett et al., 1995). At front foot contact most of the counter-rotation occurs which is reported to be in the range of 9 – 13 degrees (Elliot et al., 1992; Stockill & Bartlett, 1992a) with some results showing a counter-rotation angle of up to 40 deg (Foster et al., 1989).

The counter-rotation phase of the shoulder is an area which has received much attention due to the fact that it is one of the main causes of lumbar spine injuries in fast bowling (Elliot et al., 1992).

Non-Bowling Arm and Trunk

The non-bowling arm functions as an aiming device and assists with the rotation of the bowling limb accelerating it down and into the side of the body (Melbourne

Cricket Council, 1976). For a side-on action the arm should be placed almost vertically above the horizontal (Elliot, & Foster, 1989) so the bowler can see the batsman over the outside and inside of his arm for the front-on action. Bartlett et al. (1995) mentioned that the non-bowling arm plays an important role in executing an effective bowling action. It is important that the front leg and non-bowling arm are forced down at the same time to cause the rotation and flexion of the trunk as well as the bowling arm (Elliot, & Foster, 1989).

Ball Release and Bowling Arm

The bowling arm follows a close to normal swing pattern similar to that of sprinting until the point of back foot strike (Bartlett et al., 1995). The initiation phase of upper arm circumduction occurs between back foot and front foot strike (Bartlett et al., 1995). Bartlett et al. (1995) reported that the initiation phase of upper arm circumduction starts at the hip joint with the elbow fully extended or at a constant angle. Elliot and Foster (1989) suggested that the upper arm should be close to vertical with an angle of 200 degrees in relation to the trunk. Some studies suggest that the arm should be a little bit in front of the vertical line with an angle of close to160 degrees (Davis, & Blanksby, 1976b). Circumduction between front and back foot contact varies from bowler to bowler (Bartlett et al., 1995). Circumduction of the arm is dependent on the position of the arm at ball release as well as the position of the arm at front foot contact (Bartlett et al., 1995). Arm action is reported to contribute between 41% (Davis, & Blanksby, 1976a) to 50% (Elliot et al., 1986) of final ball release speed. Tyson (1976) suggested that the arm position at FFC can be one of the parameters providing a good prediction of what the ball release may be. The fingers and wrist are the most distal

segments of the body which contribute to the final ball release speed (Bartlett et al., 1995).

Ground Reaction Force

Newton's third law states the following: "for every action there is an opposite and equal reaction" (Hamill, & Knutzen, 2003). The vGRF is an equal and opposite force that is exerted by the ground when a person's foot strikes the ground (Liu, & Nigg, 1999; Hamil, & Knutzen, 2003). The force that the ground exerts back on the bowler during FFC in a bowling delivery stride is also described as a GRF. Forces are measured in three planes: vertical (vGRF), anterior posterior forces (Fy), and medio-lateral (Fx; Nigg, 1986; Hamill, & Knutzen, 2003). The vGRF is more commonly used or assessed in the field of biomechanics since these forces are directly related to the impact the body has to absorb (Feehery, 1986; Messier et al., 1991). The vGRF is thought to be one of the most important factors that can be related to overuse injuries (Messier et al., 1991).

The FFC phase during the delivery stride in fast/medium bowling consists of the same three GRF components (vGRF, Fy, Fx) that are examined during running. The vGRF component is again the most frequently studied component in the FFC phase in cricket due to very high impacts or loads the body has to absorb during the contact phase.

Bowling can be divided into types of front foot contact: 1) heel-toe contact and 2) flatfoot contact (Stuelcken et al., 2007). Each type of front foot contact displays a different and unique vGRF-profile (Figure 4).

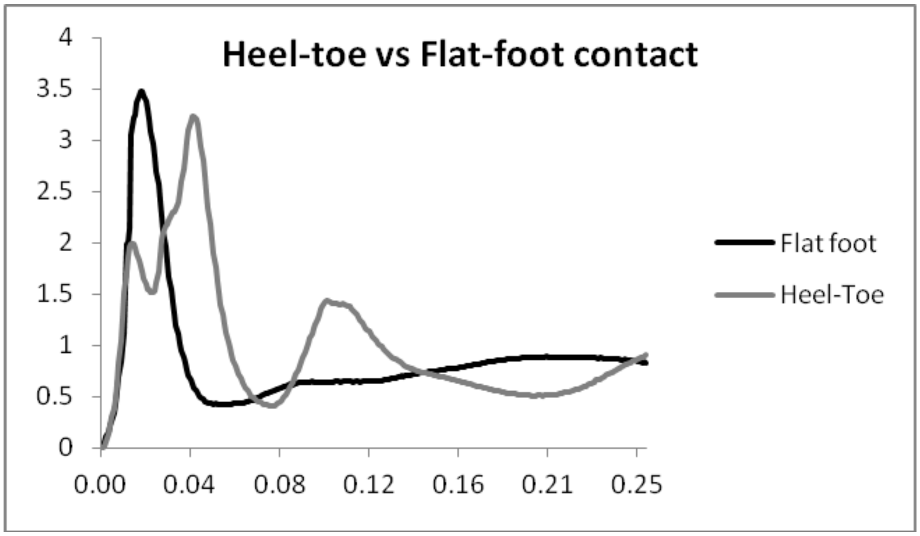

Figure 4: Vertical forces-time histories produced by heel-toe and flat foot striking pattern

The vGRF-profile of a heel-toe strike consists of two distinctive peaks (Figure 4). The first peak is referred to as the initial impact peak (F1) and is associated with initial contact of the heel of the front foot with the ground (Stuelcken, et al., 2007; Hurrion et al., 2000). The first peak (F1) occurs on average 16 ms after the heel makes contact with the ground at an average mean vertical impact force of 4.57 BW (Hurrion et al., 2000; Bartlett et al., 1996). The second peak is termed the second impact peak (F2) and is associated with front foot contact in bowling. This peak during front foot contact describes the moment when the ball of the foot comes in contact with the ground. The average time to reach F2 is 32 ms (Hurrion et al., 2000; Stuelcken, et al., 2007) with an average peak vertical force of 5.3 BW (Foster et al., 1989; Elliot, & Foster, 1984; Hurrion et al., 2000).

The vGRF-profile of a flat foot strike consists of only one distinctive peak referred to as the active peak, which displays the peak vertical force during front foot

contact (Stuelcken, & Sinclair, 2007; Hurrion et al., 2000) (Figure 4). The initial impact peak during front foot contact is not present in a flat-foot strike action (Figure 4). During a flat foot striking pattern the sole of the foot strikes the ground in a horizontal fashion causing the heel and ball of the foot to strike the ground at the same time, ultimately only displaying one combined vertical peak on the vGRF – profile (Stuelcken, & Sinclair, 2007). It takes an average of 23 ms to reach a peak vertical force during a flat foot strike pattern. Stuelcken and Sinclair (2007) graphically demonstrated that a foot flat striking pattern does have a slightly higher peak vertical force compared to a heel-toe striking pattern.

Loading Rates and Overuse Injuries

Loading rate is the time rate of force application of an object. A popular method used to calculate vertical peak impact loading rate is to divide the peak impact vertical force by the time it takes to reach the same peak impact vertical force (F1) (Hurrion et al., 2000). Peak vertical loading rate is calculated by dividing the maximum vertical force during the total foot contact phase by the time from initial heel contact to maximum vertical force (F2) (Hurrion et al., 2000). Hurrion et al. (1997b) suggested that the vertical loading rate is a more meaningful measure to use when identifying the effect of impact forces on injuries. Hurrion et al. (2000) reported mean peak impact loading rates of 300 BW.s-1. In contrast the average mean peak vertical loading rate for medium-fast male bowlers are lower (262 BW.s-1) compared to the average mean peak impact loading rate of 300 BW.s-1 (Hurrion et al., 2000; Hurrion et al., 1997b). Peak impact vertical forces may be more important to investigate when looking at causes for overuse injuries, because the higher the forces applied to the body over a short time, the higher the

possibility of injuries occurring compared to the peak vertical loading rate which is lower. The high mean peak impact loading rate and mean peak vertical loading rates may be possible indicators of the high level of injuries occurring in medium-fast bowlers (Hurrion et al., 1997b).

Shock Attenuation

A body of literature has been amassed on ground reaction force (GRF) characteristics in both back foot and front foot contact during the delivery stride in fast/medium bowlers. The topic of vGRF at front foot contact has received much attention due to the anticipated relationship to injuries in fast/medium bowlers, especially lower back injuries (Fitch, 1989; Bartlett et al., 1996). The vGRF that acts on the body at foot contact of any type of activity sends a shock wave that transmits through the body; this shock wave is also absorbed by the body in some way (Mercer et al., 2003). This notion can be applied to front foot contact in cricket. The process of absorbing the vGRF is referred to as shock attenuation (Mercer et al., 2003). Shorten and Winslow (1992) describes the vGRFs that act on the body when the foot collides with the ground as impact energy being reduced between the foot and head.

As this shock wave is transmitted through the body from the foot to the head, it forces certain musculoskeletal components together with certain joint movements to absorb as much of the shock wave (impact energy) as possible before it reaches the head where the possibility of absorbing more of the transmitted shock wave is being terminated (Derrick, 2004; Derrick et al., 1998). More specifically musculoskeletal components such as bones, muscle and soft tissue together with joint actions including

ankle, knee and hip flexion all contribute to reducing shock wave energy transmitting through the body (Valiant, 1990; Derrick et al., 1998).

Shock attenuation (SA) can be quantified by measuring the acceleration of two different segments of the body. The most common anatomical sites used in the literature include the medial aspect of the distal tibia and the forehead along the midline of the body. One method used to calculate SA is by virtue of extracting specific acceleration peaks in the time domain (Teramoto et al., 2005). The acceleration measurements from each segment (tibia and head) can be used to calculate SA and establish how much shock the body absorbed during a specific phase of action. The equation for calculating SA is as follows:

$$SA = \left(1- \frac{\text{Head Impact Acceleration}}{\text{Leg Impact Acceleration}} \right) \text{ x } 100$$

<u>Factors Possibly Affecting SA during Front Foot Contact in Bowling</u>

No current research has documented how the body absorbs impact forces during front FFC in medium or fast bowlers (Bartlett et al., 1995). Foot contact during running is a similar action to front foot contact during bowling in the sense that both actions consists of the foot striking the ground after a leg went through a swing phase before contact. Due to the limited research on SA during FFC in cricket, hypothetical assumptions will be made to describe possible factors that might influence SA during FFC in bowlers.

Ground Reaction Force

Many researchers (Lafortune et al.1995; Hamill et al. 1983; Munro et al. 1987) have stated that ground reaction forces have a direct effect on SA during running and walking. Lower extremity structures must transmit forces and shock being experienced due to vGRF acting on the body during the stance phase (Lafortune et al., 1995). Derrick et al. (1998) suggested that an increase in vGRF values (impact magnitude) cause an increase in SA during running. How the increase occurs and exactly where in the body an increase in SA occurs is currently unknown. Lafortune et al. (1995) confirmed that tibial acceleration values decrease in a linear fashion as vGRF decreases and vice versa. The vGRF acting on the body during running is on average 2-3 times BW compared to GRF during front foot contact in cricket bowling which is 3-8 times BW. Derrick et al. (1998) suggested that the higher the vertical ground reaction force (impact load) the higher the amount of shock wave energy the body absorbs. Although it is not exactly known what the cause is for overuse injuries during repeated foot contact, it is suggested that vGRF or an increase in vGRF may play a possible role in the cause of overuse injuries during repeated foot contact with the ground (Derrick et al., 1998; Messier & Pittala, 1988; Warren & Jones, 1987). If repeated foot contact with vGRF of 2-3 BW is related to overuse injuries during running (Lafortune et al., 1995), it can be assumed that repeated FFC during bowling with vGRF of 3-8 times BW will have a much greater chance of leading to overuse injuries.

Change in Knee Angle and Effective Mass During FCC

Lafortune et al. (1996) and Derrick et al. (1998) both reported that changes in lower extremity kinematics play an important role in attenuating shock during running.

Portus et al. (2004) reported the same finding in male fast bowlers. Numerous studies have shown that male fast/medium bowlers experience higher vGRF at FFC compared to bowlers who land with a bent knee at front foot contact (Portus et al., 2004; Mason et al., 1989). Several researchers (Hurrion et al., 2000; Bartlett et al., 1995; Elliot et al., 1989; and Nigg, 1983) also suggested that flexion at the knee joint during FFC would assist in reducing GRF that the body has to absorb.

Derrick et al. (1998) suggested the following logic for a flexed knee at contact absorbing more shock than an extended knee. During an extended knee the line of action progresses through the knee which results in the segments not being able to rotate about the knee joint and this ultimately cause the muscles around the knee joint to reduce or eliminate their ability to reduce any shock. In contrast, a flexed knee increases the distance causing an equivalent force to produce an increase in torque around the joint resulting in a higher angular velocity.

This increase in torque and angular velocity around the joint can be a possible cause for the muscles crossing the joint to be able to increase the amount of energy being absorbed during the eccentric contraction ultimately attenuating more shock.

Approach Velocity

Hurrion et al. (2000) suggested that the approach speed of a bowler has an effect on vGRF during FFC in bowling. Hurrion et al. (1997) reported mean peak vertical force to be higher with an increase in approach velocity. Bates et al. (1983) also reported that an increase in speed leads to an increase in vGRF during running. Further research is warranted to investigate the exact effect approach velocity has on vGRF during FFC in bowling. Investigating the effect that different running speeds have on the

vGRF during foot contact may assist in explaining the effect of different approach velocities on vGRF during FCC in bowling.

Muscle Fatigue

Gibson and Edwards (1985) defined muscle fatigue as the inability of a muscle to maintain the force during sustained or repeated muscle contractions. Muscle fatigue can be divided into central and peripheral fatigue (Powers, & Howley, 2004). Central fatigue is defined as fatigue due to a change of neuronal activity in the central nervous system. Peripheral fatigue is associated with local muscle fatigue affecting an isolated group of muscles. Mercer et al. (2003) and Derrick et al. (1998) suggest that muscle contraction potentially plays an important role in absorbing impact energy (GRF). It is not clear at present how muscle fatigue occurs and when exactly a muscle is fatigued, therefore scientists refer to possible contributors of muscle fatigue and not the exact causes of muscle fatigue.

One method of attenuating shock during foot impact is via muscle contraction and the energy-absorbing capabilities of certain anatomical structures of the body (Valiant, 1990). A strong possibility exists that these anatomical structures may be at risk to attenuate shock if the assisting muscles are fatigued (Mercer et al., 2003). Mercer et al. (2003) reported that muscles attenuated less shock when they got fatigued after running a graded exercise test. Although further research needs to be done Derrick et al. (2002) also reported that SA is influenced by fatigued muscles. If Derrick et al. (2002) and Mercer et al. (2003) reported that less shock is being attenuated during fatigued running which is a task that involves absorbing repetitive impact forces of 2-3 times BW, it can be assumed that less shock will be attenuated if muscles become fatigued over a 10

over bowling spell absorbing impact forces 3-8 times BW. Foster et al. (1998) suggested that vertical impact forces of 4-5 times BW weight at FFC or during run-up being repeated 50-60 times a day is a potential cause of overuse injuries in medium/fast bowlers due to a possible decrease in the lower extremity's ability to absorb the impact forces resulting from fatigue. Radin et al. (1979) stated that the anatomical structures and muscles may tolerate the impact forces during one single impact and still be below the tolerating threshold, but if one of these single impacts are repeated several times these impact loads may cause a potential overuse injury to specific anatomical structures.

Indoor vs. Outdoor Bowling Surfaces

Limited research has been done on what effect indoor vs. outdoor bowling surfaces have on GRF values. Hurrion et al. (1997) reported no significant differences in GRF and loading rate values between indoor and outdoor bowling surfaces despite indoor space limitations. In the study by Hurrion et al. (1997) the run-up for the indoor conditions was shorter, which resulted in a slower approach velocity due to space limitations. With this limitation in mind, it can be suspected that the vGRF and loading rate values during the indoor conditions could have been higher because of the increase in approach velocity causing a general increase in vGRF and loading rate values (Hurrion et al., 2000; Hurrion et al. 1997; Bates et al., 1983). Further research needs to be done on what effect different bowling surfaces may have on vGRF, loading rate values and SA.

Summary of Literature Review

Research has shown the immense magnitude of impact forces the body has to accommodate during FFC in bowling. Due to a demanding playing schedule which high-level cricket bowlers face, these forces may play an important role in overuse injuries. An important aspect of this issue is how the body absorbs these forces. No study to date has reported how these impact forces are absorbed during FFC. The current study was designed to assess these characteristics of performance and hopefully answer the question of how impact forces are absorbed during FFC in bowling.

CHAPTER 3

METHODS

The purpose of this study was to determine what effect bowling a 10 over spell (60 balls) would have on approach velocity, vertical ground reaction forces and shock attenuation during the front foot contact of a delivery stride in cricket.

Participants

Ten fast bowlers (age 27±4 years, height 1.78±0.3 m, mass 80.6±8.5 kg) from the Las Vegas Cricket club and/or recreational cricket players on campus volunteered for this study. The participants had no history of chronic pain, surgical intervention or any lower extremity bowling related injury. Bowlers needed at least 5 years bowling experience on an amateur level to be included in the study. Subjects were chosen for the study who displayed a natural run-up of 40 feet or closer from the delivery crease to the force platform to assure that each bowler could simulate their natural run-up in the indoor laboratory. Each bowler had a minimum average delivery speed of 90 km/h to be classified as a medium bowler, or 125 km/h to be classified as a fast bowler. Bowlers included in the study had to be able to bowl at an average speed of 90 km/h. Speed measurements where obtained with the use of a commercially available high speed radar gun. Due to the positioning of the radar gun, the speed measurements observe were more accurate the straighter the delivery is. The radar gun was positioned at the batsmen's end (Figure1) facing to the bowler in same line at which the ball is travelling. The average speed of 6 deliveries (1-over) was used to determine if the participant qualified.

Prior to study participation, subjects signed an informed consent form approved by the Institutional Review Board of the University of Nevada, Las Vegas.

Instrumentation

Kistler Force Platform

The vGRF data were measured with a force platform (1000Hz; Kistler, 9281C, SN-616902) mounted flush with the laboratory floor located in front of the bowling crease. The force platform had sensitivity level of 3.7 pC/N for measuring the vertical GRF forces. The force platform was located in such a way that the frontline (popping crease) of the bowling crease went through the middle of the force platform, perpendicular to the line of approach from the bowler (Figure 1).

Accelerometers

Two uni-axial accelerometers (1000Hz; PCB Piezotronics, model #352C68-6 and #352C68) were placed on the distal anterior-medial aspect of the tibia and on the forehead along the midline of the body to record head and leg accelerations during FFC. Both accelerometers were aligned in the vertical plane. Lueko tape was used to fit the accelerometer on the tibia and a specially made head gear was used to fit the accelerometer on the head. The Leuko tape was used to tightly to secure the accelerometers due to the high sensitivity level of the accelerometers which could be affected by soft tissue movement (Saha, & Lakes, 1977). Bioware (Version 4.02) software was used to acquire accelerometer data (2 sec).

An overhead running pulley was used to keep the wires of the accelerometers out of the way while performing the bowling delivery. The overhead pulley was safely fixed

in the opposite walls right above the bowler's head parallel to the longest wall of the laboratory. An assistant guided the accelerometer cables while the deliveries were performed to make sure that the cables did not interfere with normal motion.

Approach Velocity

An infrared timing device (Lafayette Instrument Company, 54035A) was used to record the approach velocity for each delivery. One timing light was placed at the start of the run-up and the second timing light was placed just before the delivery stride. The timing device was situated at hip level (Hurrion et al, 2000).

Figure 5: Subject being instrumented with accelerometers accompanied by the cable device.

Protocol

Data were collected in the Biomechanics indoor laboratory at the University of Nevada, Las Vegas. Three dependent variables were measured and calculated during the bowling protocol: 1) approach velocity 2) vertical ground reaction force (vGRF), and 3) shock attenuation (SA). A standard GM (manufacturers name) men's indoor cricket ball (mass 0.14-0.15 kg) was used for all bowling conditions. All participants were fitted with their own personal indoor cricket shoes for data collection. Indoor cricket shoes consist of a rubber spiked sole vs. outdoor cricket shoe which consists of a metal spiked sole that is not appropriate for indoor bowling. After subjects completed a self-directed warm-up, they started the protocol with a run-up of 12 m or closer from the force platform (due to indoor space limitations). Bowlers aimed at a set of stumps (targets) 7 m away from the bowling crease (force platform), while using their natural bowling run-up to bowl a total of 10 overs (60 balls) with an 8 minute break between each over. Each over consisted of 6 balls. After one delivery was completed the bowler walked back at normal walking pace to his original starting position ready to perform the next delivery. Each bowler was required to strike the force platform at FFC without any section of the foot being off of the force platform. Trials with partial or no contact of the front foot on the force plate were excluded from the data and not considered for statistical analysis. If a bowler missed the force platform with his front foot more than two times during one over, that specific over was excluded from data set. A minimum of 4 balls per over were needed for a successful over to be considered for data analysis. The approach velocity was measured with timing lights placed 1 m apart from each other, 2 m away from the

force platform, and perpendicular to the line of run-up. Images representing performance are given in Figures 6-8

Figure 6: Subject performing a bowling delivery during testing

Figure 7: Subject in the pre-delivery phase of the bowling action

Figure 8: A view from the rear illustrating the indoor testing conditions

Data Reduction

Kinetic parameters of the FFC during each bowling trial were extracted. GRF and accelerometer data were converted to text files and processed manually using Excel software. The peak vGRF, peak leg acceleration and peak head acceleration were all the parameters extracted from each bowling trial. The criteria for extracting accelerometer data were made relative to the second peak in the leg acceleration profile. Exemplar vGRF and acceleration time-histories are given in Figure 9-11. The peak leg acceleration and peak head acceleration values were extracted to quantify SA between two segments using the following the following equation.

$$SA = \left[1 - \frac{\text{Head Impact Acceleration}}{\text{Leg Impact Acceleration}} \right] \times 100$$

The mean values across 6 trials for each parameter were calculated for each condition (over).

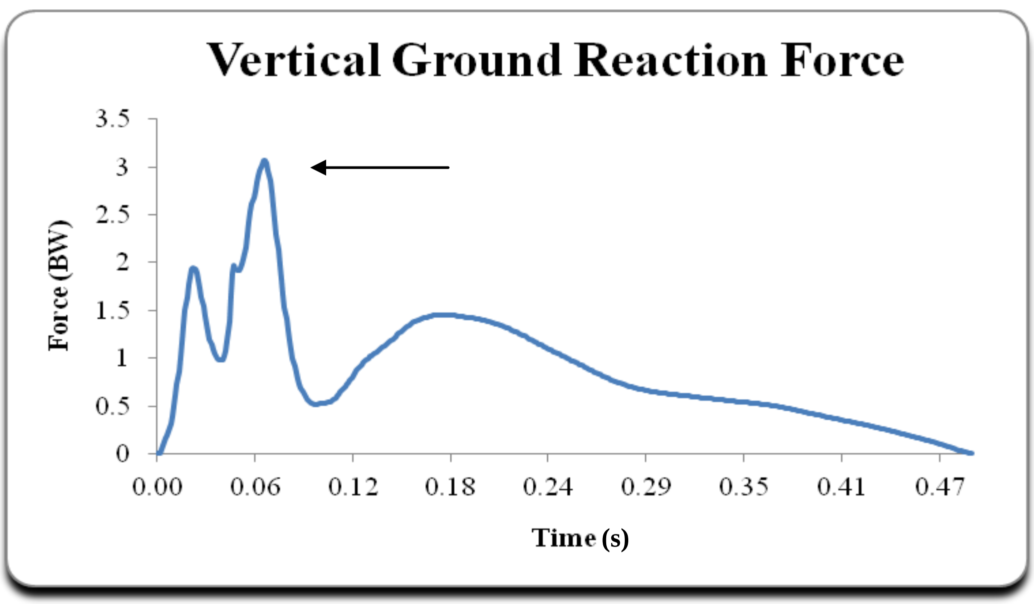

Figure 9: Exemplar peak vertical force used for analyzing data.

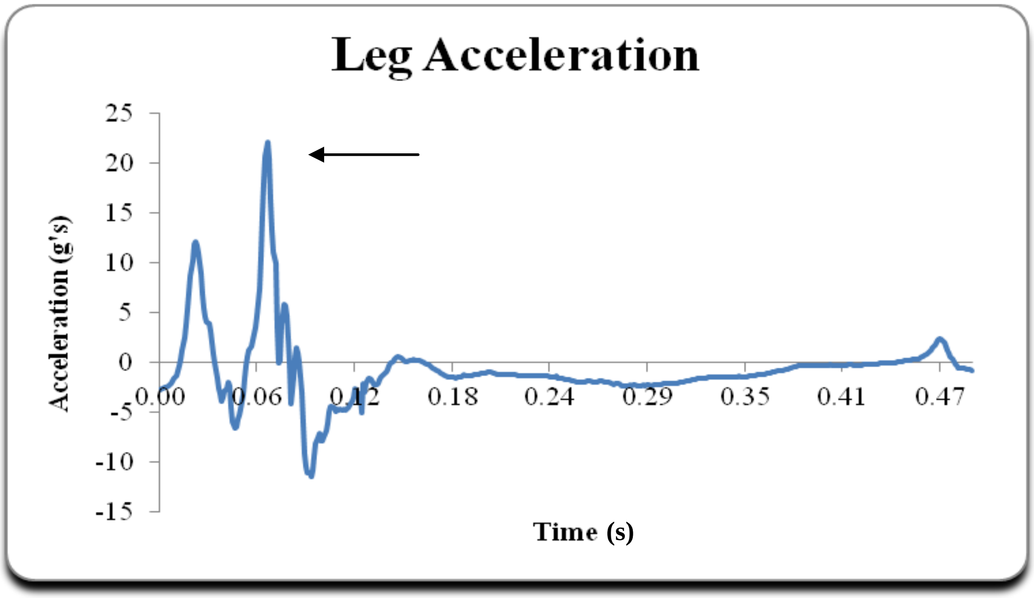

Figure 10: Exemplar leg impact accelaration peaks identified for quantifying SA.

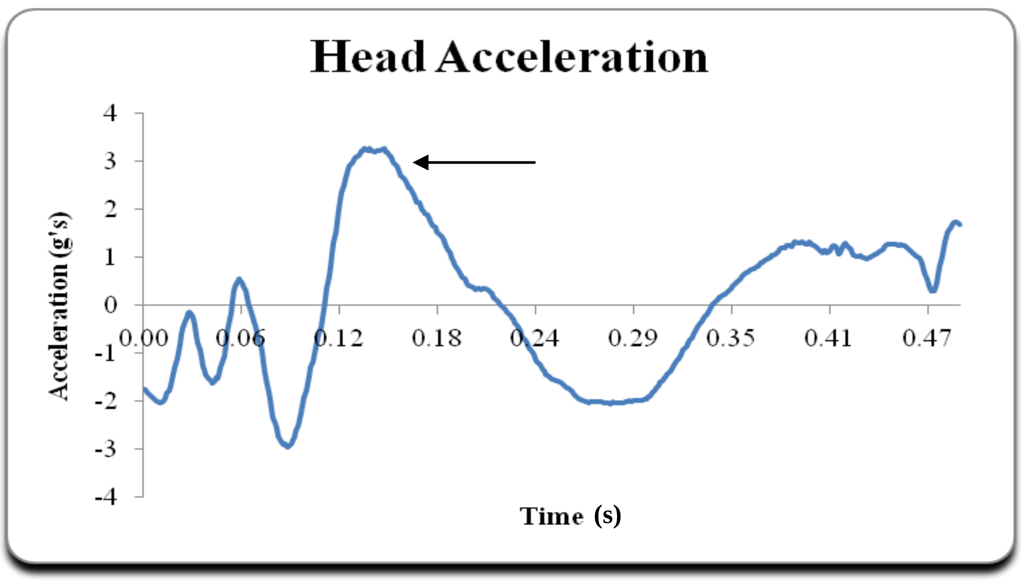

Figure11: Exemplar head impact acceleration peak identified for quantifying SA.

Data Analysis

A one way repeated measures ANOVA study design was used to analyze the data. (For statistical analyses, overs were combined into 3 groups namely: overs 1&2 (beginning), overs 5&6 (middle) and overs 9&10 (end)). The factor was “group number” (between groups 1, 2 and 3) being within subjects. The dependent variables of interest were approach velocity (APV), vGRF and SA. The independent variable of interest was time (number of overs). The alpha level was set at 0.05. A planned comparisons test between beginning to middle and middle to end was used to identify the source of differences if the main effect was significant. SPSS for Windows (release16) was used for statistical analysis.

CHAPTER 4

RESULTS

The purpose of this study was to determine what effect bowling a 10 over spell (60 balls) would have on approach velocity, maximum vertical ground reaction force (vGRF) and shock attenuation (SA) during the front foot contact of a delivery stride in cricket.

Descriptive Statistics

Ten amateur cricket bowlers from the Las Vegas Cricket Club performed 10 overs with 8 min rest between overs. No overs were excluded during the protocol due to a subject missing the force platform more than twice in one over.

A visual examination of results for all three dependent variables namely APV, vGRF and SA suggested they did not stay the same across bowling 10 overs. The mean and standard deviation values across subjects for each dependent variable are given in Table 2 and are represented graphically in Figures 12-14. Individual mean and standard deviation values for each variable across all 10 overs for all 10 subjects are illustrated in Tables 3-7 (Appendix II).

Table 2: Mean and standard deviation values for all variables by each over

Variable	APV	vGRF	PLeg	PHead	SA
O1	4.73±0.05	3.96±0.51	24.96±5.15	4.32±0.74	78.06±5.79
O2	5.03±0.09	4.11±0.423	26.64±4.94	4.50±0.70	77.07±5.65
O3	5.24±0.11	4.01±0.45	26.71±5.99	4.26±0.52	78.44±5.15
O4	5.12±0.12	4.15±0.33	29.13±5.82	4.32±0.71	78.53±5.90
O5	5.55±0.06	4.17±0.52	32.06±7.98	4.28±0.74	80.485±5.96
O6	5.74±0.06	4.02±0.36	28.69±5.84	4.45±0.42	79.66±4.51
O7	5.57±0.06	4.02±0.47	29.41±6.18	4.21±0.53	80.88±4.45
O8	5.41±0.10	3.79±0.45	26.40±5.29	4.40±0.59	77.59±6.19
O9	5.09±0.08	3.79±0.38	26.56±4.89	4.38±0.65	79.31±31
O10	0.82±0.07	3.73±0.39	26.88±4.99	4.30±0.54	78.95±5.60

Note: O = over (e.g., O1 = over 1)

Approach Velocity

Average approach velocity of all 10 subjects combined demonstrated an increase of 1.09 m/s from over 1 through over 6 with a decrease of 1.5 m/s from over 6 to over 10 (Figure 12). A decrease of 0.15 m/s was observed from over 3 to over 4. A maximum average approach velocity across subjects of 5.40 m/s occurred during over 6 and a minimum average velocity of 3.88 m/s occurred at over 10.

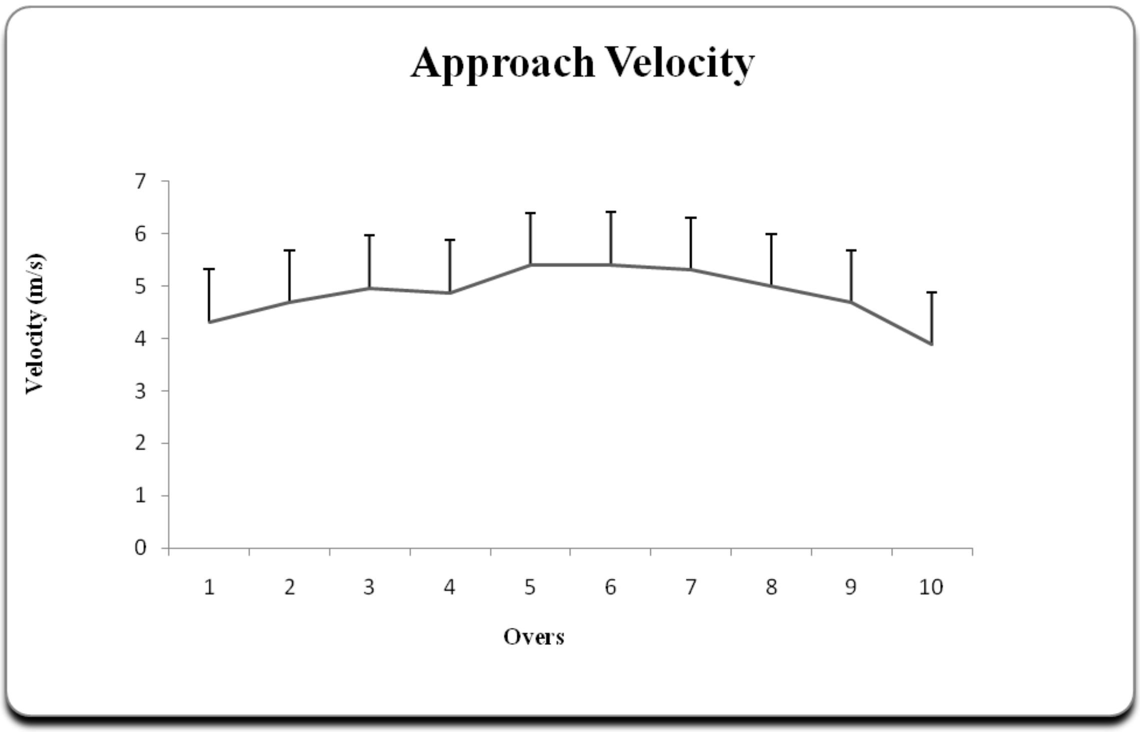

Figure 12: Average approach velocity of all 10 subjects across 10 overs.
Vertical bars represent 1 standard deviation.

Vertical Ground Reaction Force

An increase of 0.2 BW occurred from over 1 to over 5 (Figure 13). A decrease of 0.4 BW occurred from over 5 to over 10. Maximum average vGRF of 4.1 BW occurred at over 5 and minumum vGRF of 3.7 BW occured at over 10.

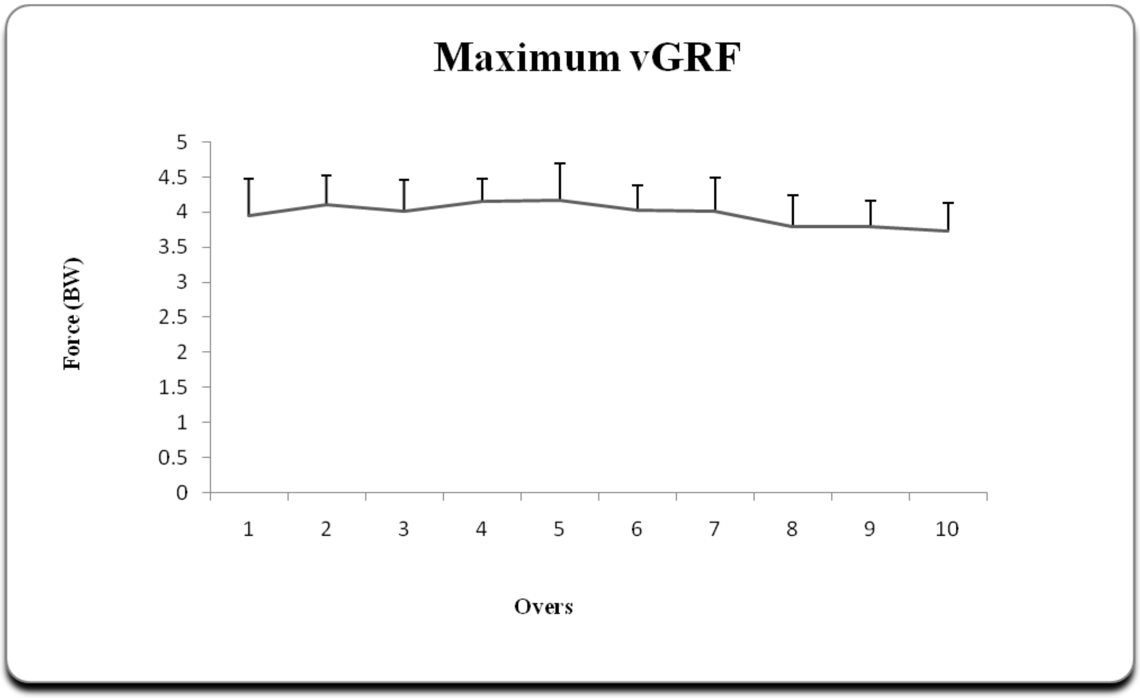

Figure 13: Average vGRF across 10 overs for all 10 subjects combined. Vertical bars represent 1 standard deviation.

Shock Attenuation

Average SA showed slightly greater variable increases and decreases in values between each over compared to other variables (Figure 14). A increase of 2.8% occurred from over 1 to over 7 (Figure 13). A decrease of 1.9% occurred from over 7 to over 10. Maximum average SA of 80.9% occurred at over 7 and minumum SA of 77.1% occured at over 2.

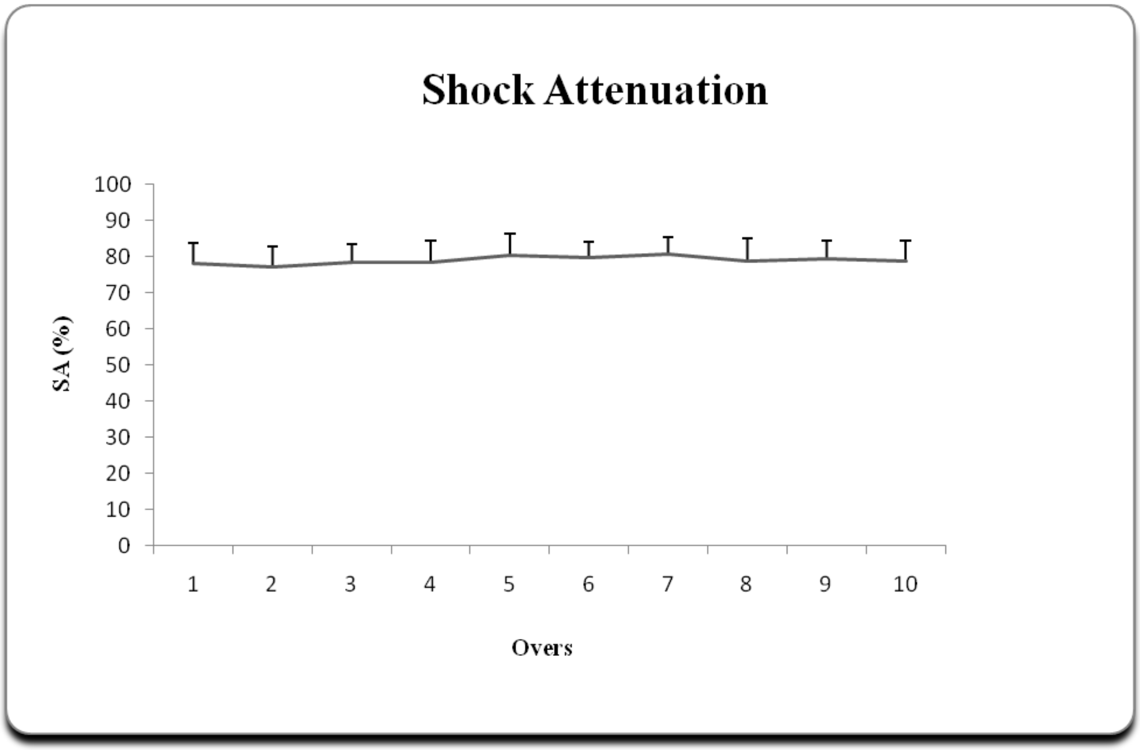

Figure 14: Average SA (%) across 10 overs for all 10 subjects combined.
Vertical bars represent 1 standard deviation.

The effects that "time" had on performance (the effect of bowling 10 overs) explored in greater depth. Therefore, data were grouped into sets of two overs representing the beginning, middle and ending of the performance. The mean values for each phase of the overs were calculated. These data are presented in Table 7 and show that approach velocity (APV) increased from the begining to middle with a greater decrease in speed from the middle to end. The vGRF showed a smaller increase from the begining to middle compared to a larger decrease from the middle to the end. SA showed larger increase from beginning to middle compared to a smaller decrease from middle to end.

Table 8 – Descriptive statistics: Mean and standard deviations for dependent variables

	Over 1& 2	Over 5 & 6	Over 9 & 10
Approach Velocity (m/s)	4.34 ± 1.32	5.18 ± 1.42	4.13 ± 1.27
vGRF (BW)	4.03 ± 0.69	4.09 ± 0.81	3.76 ± 0.58
Peak Leg (g)	25.58 ± 14.37	31.39 ± 18.52	26.33 ± 13.24
Peak Head (g)	4.34 ± 1.13	4.28 ± 1.04	4.31 ± 0.95
SA (%)	77.18 ± 11.26	79.34 ± 10.52	78.39 ± 10.5

Time Duration to Complete Overs

Time between overs was carefully controlled in this study (8min) . However , the total time taken to complete each over was free to vary. Average time to complete each over is given in Table 9. It can be observed that over 5 was completed the fastest

Table 9 – Average approach velocity for all 10 subjects for each over

Over	1	2	3	4	5	6	7	8	9	10
Time (Min)	4.9	4.2	3.1	3.8	2.9	5.2	5.5	5.0	4.8	5.2

Inferential Statistics

Significant overall differences ($p<0.05$) were found across the 10 over bowling spell in all three variables of interest: APV ($p<0.05$), vGRF ($p<0.05$), and SA ($p<0.05$). Significant values are presented in Table 10.

Table 10 – Repeated Measures ANOVA - Summary (overall significance)

Source	APV		vGRF		Peak Leg		Peak Head		SA	
	F	p	F	p	F	p	F	p	F	p
Over	10.023	0.001*	4.595	0.024*	4.393	0.028*	0.465	0.635	4.196	0.032*

* ($p \leq 0.05$)

Inferential statistics were performed using the group data as stated previously. A significant difference was observed for APV between the beginning (4.34 ± 1.22 m/s) and middle (5.18 ± 1.42 m/s) as well as a significant difference between middle (5.18 ± 1.42) and end (4.13 ± 1.27 m/s). The vGRF results illustrated a significant difference ($p>0.05$) between the middle (4.09 ± 0.81 BW) and the end (3.76 ± 0.58 BW). No significant difference ($p<0.05$) was found between the beginning (4.03 ± 0.69) and the middle (4.09 ± 0.81BW). An overall significant difference was found in SA across all 10 overs. A significant difference was found between the middle (79.48 ± 10.43%) and the end (78.23 ± 10.72%) as well as between beginning and end. These results are summarized in Table 11.

Table 11 – Repeated Measures ANOVA Summary (Planned comparisons)

Source	APV	vGRF	Peak Leg	Peak Head	SA
	p	p	p	p	p
O1 & 2 vs. O5 & 6					
Planned comparisons	0.009*	0.513	0.008*	0.744	0.019*
O5 & 6 vs. O9 & 10					
Planned comparisons	0.001*	0.035*	0.093	0.310	0.050*

* ($p \leq 0.05$)

CHAPTER 5

DISCUSSION

The purpose of this study was to determine what effect bowling a 10 over spell (60 balls) would have on approach velocity, maximum vertical ground reaction force and shock attenuation during the front foot contact of a delivery stride in cricket. This was accomplished by bowling 10 consecutive overs with an 8 min rest between overs. Subjects bowled from a 12 m run-up and contacted the force platform with the front foot to obtain vGRF data. Shock attenuation was calculated from acceleration values obtained from two accelerometers placed on the tibia and head, respectively. Approach velocity was measured using two timing lights placed one meter apart from each other, two meters away from the force platform.

Research suggests that high vGRFs, between 2-9 times BW, are generated at front foot contact (FFC) during the delivery stride of the bowling action in male cricket bowlers (Stuelcken et al., 2007; Hurrion et al., 2000; Elliot & Foster, 1984; & Mason et al., 1989). Cricket literature has put forth a general belief that the high magnitudes of vGRF generated at FFC may play an important role in the occurrence of overuse injuries in male fast bowlers (Stuelcken et al., 2007; Hurrion et al., 2000; Fitch, 1989). The vGRF produced at foot contact causes a shock wave of impact energy that travels through the body up to the head. It is conjectured that the body needs to attenuate this impact energy in some way in order to minimize injury potential.

Other research has shown that high vGRFs are produced at FFC. It has also been suggested that these vGRFs may play a role in overuse injuries (Stuelcken et al., 2007; Hurrion et al., 2000; Elliot & Foster, 1984; & Mason et al., 1989).

To date no study has addressed what happens to the vGRF over a period of bowling multiple overs consecutively. Such information would contribute to better understand how these vGRFs are attenuated over bowling multiple overs consecutively.

The current study was designed to focus on the need to provide the groundwork to address both of these previously stated questions. It is clear that further research needs to be done to better understand both the concepts of vGRF over a period of time and the body's ability to attenuate these forces during a 10 over spell in cricket bowling.

Why a 10 Over Bowling Spell?

During international cricket matches, the maximum amount of overs a fast/medium bowler bowls consecutively ranges on average between 7 to10 overs. If a bowler performs well in the first 7 overs and the tactical plan of the game promotes the idea, a bowler may continue and complete a 10 over spell without having a break. During a longer version of the game (test cricket) played over 5 days, there is no limit to how many overs a bowler bowls consecutively, ultimately causing the fast/medium bowler to bowl longer spells of 10 overs or more, especially if the bowler is performing well. During strenuous practice sessions bowlers bowl a great amount of balls that sum to close to 10 overs. This study attempted to simulate these conditions to establish if bowling long spells can possibly contribute to overuse injuries by placing too much stress on the body by bowling to many consecutive overs.

Limitations to Consider in the Current Study

The participants in this study were at amateur level, with a reasonable level of fitness and active lifestyles. Due to geographical limitations it was not possible to include elite international players. Elite cricket players might have had an increase in

vGRFs and approach velocities during data collection. The other important factor to take into account was the fitness level of elite players, which would have likely been higher than the bowlers used in this study. The level of fitness might have contributed to a change in general tiredness level during the bowling protocol.

Approach Velocity

The current study showed that the bowlers had a significant increase from the beginning (over 1&2; 4.47 ± 1.22 m/s) to the middle (over 5&6; 5.49 ± 1.28 m/s). A significant decrease from the middle (over 5&6; 5.49 ± 1.28 m/s) to end (over 9&10; 4.40 ± 1.23 m/s) was also observed. These results lead to the following possibilities: 1) an average fast bowler has a build-up phase at the beginning of his bowling spell reaching peak ball speed/intensity in the middle of the bowling spell and ultimately decreasing ball speed/intensity at the end of the bowling spell, and 2) possible general tiredness. On average a fast bowler takes between 2 to 4 overs to reach maximum performance, as evidenced by approach velocity as well as maximum ball speed during a cricket game. It would be reasonable to assume that an increase in bowling speed and performance would require an increase in APV. In addition, a significant decrease in velocity was found between the middle (5.49 ± 1.28 m/s) and the end (4.13 ± 1.27). This decrease may be strongly related to general because bowlers were reaching the end (4.40 ± 1.23 m/s) of the bowling spell.

There should be no reason for a fast/medium bowler to reduce his APV if he was performing well (good rhythm, ball speed and performance). According to the literature, it has been observed that vGRFs increased as APV increased during bowling in fast/medium bowlers (Hurrion et al, 1997). Bates et al., (1983) also reported that an

increase in speed resulted in an increase in vGRFs when running. The current study showed similar results in that both APV and vGRF significantly decreased from the middle to end. Although vGRF did not show a significant increase from beginning to middle, a slight increase was still visible. This slight increase was accompanied by a significant increase in APV from beginning to middle. These findings suggest that APV may play an important role in how much vGRF is produced at FFC in cricket bowling and ulitimity having a possible affect in the amount of impact energy the body has to absorb during FFC in cricket bowling.

Vertical Ground Reaction Forces

The vGRF values showed an overall significant difference across the 10 over bowling spell. A significant difference was found between the middle (4.09 ± 0.81 BW) and the end (3.76 ± 0.58 BW) with no significant difference between the beginning (4.03 ± 0.69 BW) and the middle (4.09 ± 0.81 BW). These findings support the idea that bowlers could reach a stage of general tiredness between the middle and end of 10 overs and that a decrease in APV may contribute to this decrease in vGRF. Although it is difficult to determine when exactly the muscles reached a point of general tiredness, an assumption can be made that the muscles were not able to produce the same magnitudes of force at front foot contact compared to being in a state of no general tiredness. Another possible reason that might contribute to the observed reduction in vGRFs over the last 5 overs was the different theoretical paths that Nordin and Franklin (2001) suggest which might lead to overuse injuries (Figure 2).

Nordin and Franklin (2001) suggested that after the muscles fatigue, the mechanics of a certain action (e.g. bowling) may change. If this is the case in the current

study, the bowler's muscles might have fatigued or reached a state of general tiredness, which caused a change in bowling mechanics, leading to a possible change in the way the bowler makes contact with the ground resulting in a change or decrease of vGRF (Figure 3). If the muscles reached a point of general tiredness during the last 5 overs, it can be suggested that reduced vGRF resulted in a reduction in the amount of impact energy that the body had to absorb. It is important to note that fatigue was not directly measured in this study and that this discussion is only conceptual.

Shock Attenuation

An overall significant difference was found in SA across all 10 overs. A significant difference was also illustrated between the middle (79.48 ± 10.43%) and the end (78.23 ± 10.72%). To better understand SA results, PLeg and PHead accelerations profiles were examined (Figures 15-16). The significance found in PLeg acceleration (Table 10) across the 10 over spell compared with no significance observed in PHead acceleration (Table 10). Peak leg acceleration (PLeg) values showed a significant increase from begining to the end and a significant decrease was observed from the middle to the end. Peak head acceleration (PHead) values showed a (Figure 15-16) constant pattern with no significant decrease across all three levels of time. These findings support the notion that the body adjusted to accommodate an increase in PLeg acceleration (impact magnitude). Derrick et al. (1998) suggested and supported the same concept. An overall significant difference found in leg acceleration compared to a significant difference found in head acceleration indicates that PLeg acceleration was the component in the formula used to calculate SA that drove the change in SA values. This correlates with the findings of Derrick et al. (2002) where Pleg acceleration values were

also the component that drove the significance change in SA values. A contradicting finding was observed by Mercer et al. (2003) that showed no significant changes in PLeg and PHead acceleration but still finding a significant decrease in SA values.

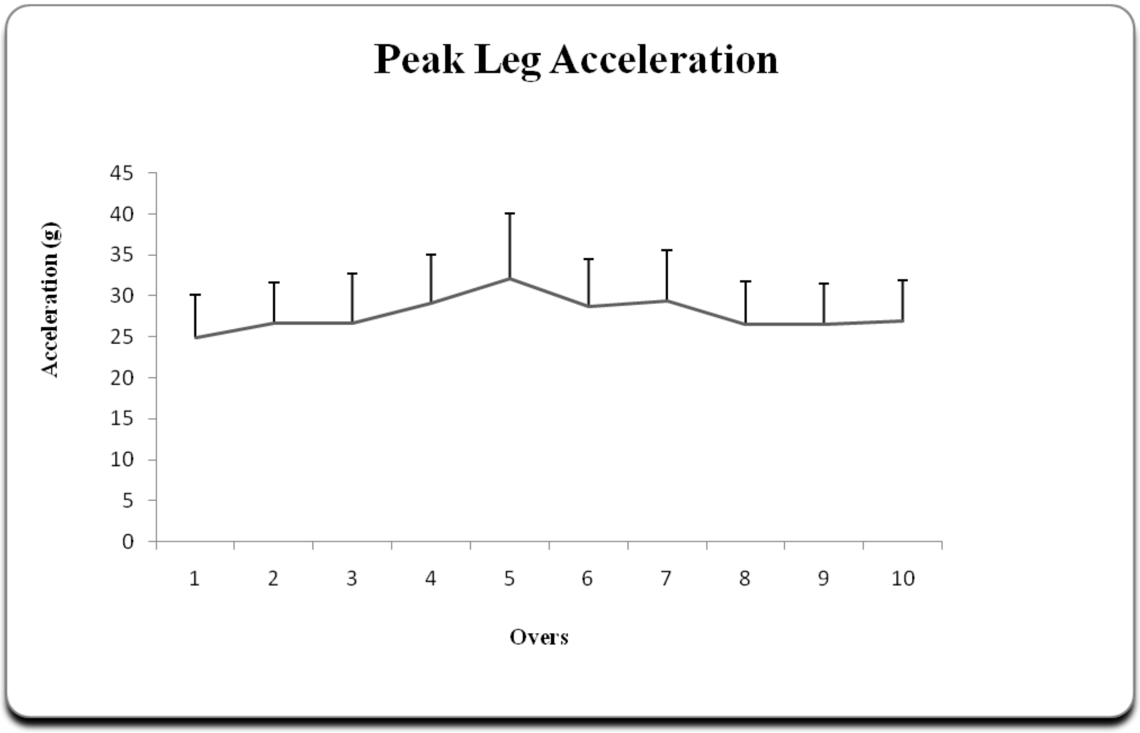

Figure 15: Average PLeg across 10 overs for all 10 subjects combined. Vertical bars represent 1 standard deviation.

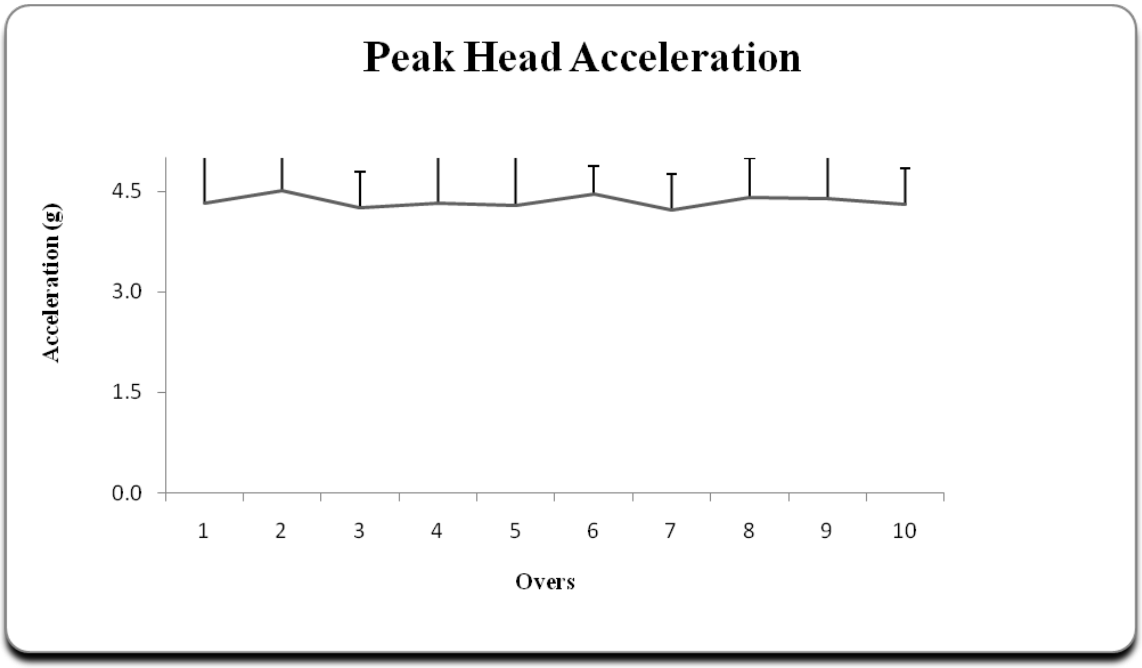

Figure 16: Average PHead across 10 overs for all 10 subjects combined. Vertical bars represent 1 standard deviation.

Another important factor to consider was that the magnitude of SA produced showed high standard deviation values among subjects for each individual over. An average standard deviation of ± 5.43% across all 10-overs for all 10 subjects was observed. These high standard deviation values strongly suggest the way each bowler attenuated the shock varied greatly and/or that bowlers performed with unique strategies.

This high variability among subjects could be better addressed by using single subject analyses which might result in identification of unique bowling strategies. This idea is supported by fast/medium bowlers having different bowling actions in general with a focus on lower extremity kinematics. Examples of these observed differences in lower extremity kinematics between subjects are an extended knee at FFC vs.a flexed knee at FFC and a difference in the orientation of the front foot at FFC.

Results Relative to Performance

The "bigger picture" or purpose of this study was to investigate questions regarding relative kinetics of FFC in fast/medium bowlers to gain a better understanding of how overuse injuries occur in fast/medium bowlers. This study contributes useful information to the world of cricket which can be taken into account as possible factors which could reduce the occurrence of overuse injuries in fast/medium bowlers. Several researchers conducted studies on vGRFs and APV over a short number of balls (Foster et al., 1989; Elliott, & Foster, 1984; Hurrion et al., 2000), but no research has been done on what effect a 10 over bowling spell will have on vGRF, APV or SA. The majority of the time fast/medium bowlers bowl between 6 and 10 overs consecutively in a normal 1 day or 5 day cricket match. Therefore, this study was conducted simulating real life scenarios aimed at applying the results to more real bowling conditions (i.e. matches and practice). It is known that the body has to attenuate high vGRFs during bowling (Foster et al., 1989; Elliot, & Foster, 1984; Hurrion et al., 2000). These high vGRFs cannot be avoided due to the nature of the action, however the duration period of the applied vGRF can be controlled by selecting how many overs a bowler can continuously bowl without a break.

In cricket, much focus is placed on protecting bowlers from bowling too many balls or overs during a season. The author believes that it is of utmost importance for a bowler to not bowl too many balls or overs in one bowling session or spell, to prevent moving into a possible danger zone, where the body is more prone to injury. This being said, a continuum was establish for this current study and future research to better explain the effect of long bowling spells on vGRF and SA (Figure 17).

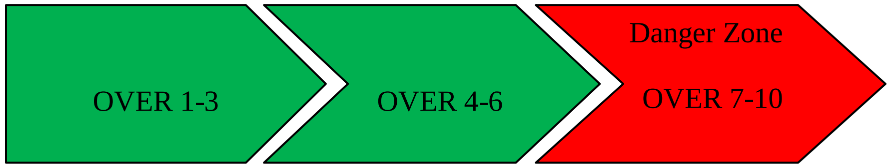

Figure 17: Hypothetical diagram indicating possible danger zone for bowlers to acquire overuse injuries

This study emphasized new ideas, because it is important for a bowler to realize when his body is close to entering a danger zone during a single practice session or bowling spell where the body looses the ability to attenuate the high magnitudes of vGRFs produced during FFC in fast/medium bowlers. Another important factor to focus on is the fact that each bowler may have different bowling actions due to different kinematics observed during the delivery stride. If a coach or conditioning specialist can have a more accurate idea of where during a bowling spell the body starts losing its ability to attenuate shock, it may help prevent overuse injuries in fast/medium bowlers.

Future Research

This current study provided groundwork in order to better understand how APV, vGRF and SA patterns change over a period of 10 overs. Due to great variability observed among subjects (standard deviation ± 5.43% in SA results), future research on how the kinematics of each individual bowler may affect the body's ability to produce vGRF at FCC as well as attenuate the shock produced by the vGRF should be investigated. Due to space and level of skill limitations, better understanding might be provided if elite players are used with a more natural run-up condition.

Conclusion

It is well documented that high magnitudes of vGRFs are produced during FFC in fast/medium bowlers (Stuelcken et al., 2007; Hurrion et al., 2000; Elliot & Foster, 1984; & Mason et al., 1989). Researchers suggested that these high vGRFs may play an important role in overuse injuries if the bowler performs too many bowling deliveries over a season. The purpose of this study was to determine what effect bowling a 10 over spell (60 balls) would have on approach velocity, maximum vertical ground reaction force and shock attenuation during the front foot contact of a delivery stride in cricket. It was observed that APV, vGRF and SA all showed a change over time (number of overs). The exact mechanisms of overuse injuries in cricket are not fully understood, but this study suggested that repetitive contact with the ground at FFC generates high forces between the foot and ground which could play an important role as a contributing factor to overuse injuries in fast/medium bowlers. Researchers including Lafortune et al.1995; Hamill et al. 1983; Munro et al. 1987 have stated that ground reaction forces have a direct effect on SA during running and walking. This suggests that vGRF may have an effect on SA in bowling as well. A significant difference was found between beginning and middle in SA compared to no significance in vGRF from beginning to middle as well as a weak significance found ($p<0.05$) from middle to end in SA compared to a strong significance found between middle and end in vGRF. These findings suggests that further investigation needs to be done to attempt to establish what the cause for this relationship between these two variables are since the literature suggest a strong interaction between vGRF and SA.

APPENDIX I

IRB FORMS

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

UNLV IRB Approved FEB 10 2010 Expires FEB 09 2011

Biomedical IRB – Expedited Review
Approval Notice

NOTICE TO ALL RESEARCHERS:

Please be aware that a protocol violation (e.g., failure to submit a modification for any change) of an IRB approved protocol may result in mandatory remedial education, additional audits, re-consenting subjects, researcher probation suspension of any research protocol at issue, suspension of additional existing research protocols, invalidation of all research conducted under the research protocol at issue, and further appropriate consequences as determined by the IRB and the Institutional Officer.

DATE: February 16, 2010

TO: **Dr. Janet Dufek**, Kinesiology

FROM: Office for the Protection of Research Subjects

RE: Notification of IRB Action by Dr. John Mercer, Chair
Protocol Title: **The Effect of a 10-Over Bowling Spell On a Vertical Ground Reaction Forces and Shock Attentuation In Medium Cricket Bowlers**
Protocol #: 1001-3329

This memorandum is notification that the project referenced above has been reviewed by the UNLV Biomedical Institutional Review Board (IRB) as indicated in regulatory statutes 45 CFR 46. The protocol has been reviewed and approved.

The protocol is approved for a period of one year from the date of IRB approval. The expiration date of this protocol is February 9, 2011. Work on the project may begin as soon as you receive written notification from the Office for the Protection of Research Subjects (OPRS).

PLEASE NOTE:
Attached to this approval notice is the **official Informed Consent/Assent (IC/IA) Form** for this study. The IC/IA contains an official approval stamp. Only copies of this official IC/IA form may be used when obtaining consent. Please keep the original for your records.

Should there be *any* change to the protocol, it will be necessary to submit a **Modification Form** through OPRS. No changes may be made to the existing protocol until modifications have been approved by the IRB.

Should the use of human subjects described in this protocol continue beyond February 9, 2011 it would be necessary to submit a **Continuing Review Request Form** *60 days* before the expiration date.

If you have questions or require any assistance, please contact the Office for the Protection of Research Subjects at OPRSHumanSubjects@unlv.edu or call 895-2794.

Office for the Protection of Research Subjects
4505 Maryland Parkway • Box 451047 • Las Vegas, Nevada 89154-1047

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

Informed Consent

Department of Kinesiology and Nutrition Sciences

TITLE OF STUDY: The Effect of a 10-Over Bowling Spell on Vertical Ground Reaction Forces and Shock Attentuation in Medium Cricket Bowlers

INVESTIGATOR(S): Dr. Janet Dufek Ph.D.

CONTACT PHONE NUMBER: 702-895-0702

Purpose of the Study

You are invited to participate in a research study. The purpose of this study is The purpose of this study is to determine what effect bowling a 10-over spell (60 balls) will have on vertical ground reaction forces and shock attenuation during the front foot contact of a delivery stride in cricket.

Participants

You are being asked to participate in the study because you are a male between 20 and 35 years old, you are a healthy active person and you are comfortable and fit enough to be able to bowl a 10 over spell. You must have at least 5 years of bowling experience at club level. You will not be able to participate if you have any injury that makes bowling difficult or if you are not able to bowl a 10 over spell.

Procedures

If you volunteer to participate in this study, you will be asked to do the following: You will be asked to attend two pre-test sessions and later complete a 10-over bowling spell. At the first orientation session, we will measure the speed of your bowling with an external measurement device. If you are able to bowl at a speed fast enough for our study, you will be invited to attend pre-test session two. At this time, you will be allowed to practice bowling in the laboratory environment. If you are comfortable performing in this setting, you will be invited to return to the laboratory to complete a 10-over bowling spell. Prior to activity, you will be allowed to warm up, and then small measurement devices will be attached externally to your leg and head. You will then be asked to perform a minimum of 2 and maximum of 4 deliveries with all the equipment attached to make sure you are comfortable bowling with the equipment attached to your body. After the 10-over spell is completed you will be given a chance to perform a self-directed cool-down.

Participant Initials: __________

Benefits of Participation

There may not be direct benefits to you as a participant in this study. However, we hope to learn more about what role ground reaction forces and shock attenuation may play in overuse injuries during prolonged medium or fast bowling.

Risks of Participation

There are risks involved in all research studies. This study may include only minimal risks. The primary risks are muscle cramps and soreness after bowling the 10 overs. To minimize muscle soreness, you will be given time to warm up and cool down. Water will be provided between overs as needed and you will be allowed to stretch for 1 minute between overs. Any precaution that you take to prevent muscle soreness, stiffness or cramps during a normal game will be allowed during the 10-over spell.

Cost /Compensation

There will not be financial cost to you to participate in this study. The study will take 2 hours of your time. You will not be compensated for your time.

Contact Information

If you have any questions or concerns about the study, you may contact Dr. Janet Dufek at 702-895-0702 . Jaco Liebenberg at 702-806-7288

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted you may contact the **UNLV Office for the Protection of Research Subjects at 702-895-2794 or toll free at 877-895-2794**.

Voluntary Participation

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with the university. You are encouraged to ask questions about this study at the beginning or any time during the research study.

Confidentiality

All information gathered in this study will be kept completely confidential. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be shredded if in paper form and deleted/destroyed if electronic media.

Participant Consent:

Participant Initials: _________

Protocol Title: The Effect of a 10-Over Bowling Spell on Vertical Ground Reaction Forces and Shock Attenuation in Medium

UNLV IRB Approved FEB 1 0 2010 Expires FEB 0 9 2011

I have read the above information and agree to participate in this study. I am at least 20 years of age. A copy of this form has been given to me.

Signature of Participant ______________________ Date ______________

Participant Name (Please Print) ______________________

Audio/Video Taping
This study involves Audio/ Video Taping.

Hereby I agree to be taped while I perform the bowling protocol.

Signature of Participant ______________________ Date ______________

Participant Name (Please Print) ______________________

Participant Note: Please do not sign this document if the Approval Stamp is missing or is expired.

Participant Initials: ________

Page 3 of 3

APPENDIX II

INDIVIDUAL SUBJECT DATA

Table 3 – Individual vGRF averages and standard deviations for each subject across 10 overs.

		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Subject 9	Subject 10	Average
Over 1	**AVG**	3.56	3.26	4.17	2.98	3.54	5.04	4.25	4.46	3.87	4.46	3.96
	STDEV	0.22	0.43	0.35	0.27	0.08	0.39	0.73	1.69	0.10	0.84	0.51
Over 2	**AVG**	3.43	3.54	3.89	3.11	3.55	4.95	4.27	5.21	3.77	5.34	4.11
	STDEV	0.50	0.44	0.53	0.18	0.05	0.26	0.60	0.80	0.25	0.63	0.42
Over 3	**AVG**	3.54	3.47	3.64	2.79	3.45	4.79	4.17	5.02	3.92	5.37	4.01
	STDEV	0.55	0.24	0.55	0.19	0.17	0.33	0.72	0.68	0.26	0.84	0.45
Over 4	**AVG**	3.65	3.66	3.51	2.52	3.31	5.06	4.20	5.89	3.96	5.78	4.15
	STDEV	0.17	0.32	0.43	0.29	0.25	0.27	0.86	0.16	0.28	0.22	0.33
Over 5	**AVG**	3.38	3.71	3.80	2.96	3.42	4.52	4.42	5.54	4.24	5.67	4.17
	STDEV	0.27	0.33	0.51	0.56	0.17	0.63	0.78	0.74	0.28	0.95	0.52
Over 6	**AVG**	3.52	3.44	3.89	3.07	3.27	4.54	4.63	4.91	3.83	5.18	4.03
	STDEV	0.16	0.29	0.69	0.18	0.31	0.53	0.17	0.29	0.30	0.67	0.36
Over 7	**AVG**	3.53	3.59	3.15	2.95	3.30	4.37	4.67	5.19	4.09	5.32	4.02
	STDEV	0.19	0.36	0.75	0.39	0.36	0.64	0.44	0.61	0.28	0.75	0.48
Over 8	**AVG**	3.41	3.66	2.96	3.21	3.29	4.27	4.08	4.25	3.94	4.85	3.79
	STDEV	0.25	0.43	0.24	0.08	0.28	0.57	0.58	0.88	0.35	0.82	0.45
Over 9	**AVG**	3.40	3.44	2.85	3.28	3.37	4.47	4.12	4.33	4.02	4.60	3.79
	STDEV	0.38	0.24	0.39	0.14	0.27	0.60	0.30	0.47	0.17	0.80	0.38
Over 10	**AVG**	3.57	3.22	3.02	3.14	3.33	4.48	3.95	4.21	3.82	4.61	3.73
	STDEV	0.27	0.30	0.29	0.32	0.30	0.32	0.26	0.36	0.70	0.78	0.39

Table 4 – Individual average peak leg acceleration averages and standard deviations for each subject across 10 overs.

		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Subject 9	Subject 10	Average
Over 1	**AVG**	15.38	16.98	22.15	14.97	15.52	43.17	16.85	53.92	11.93	29.10	24.96
	STDEV	5.73	2.07	5.69	4.29	2.13	6.97	1.51	18.36	1.92	3.44	5.15
Over 2	**AVG**	16.24	24.21	21.29	13.66	12.04	46.56	18.33	59.07	15.38	29.29	26.65
	STDEV	3.71	4.71	3.06	3.45	2.45	5.46	3.88	10.64	5.73	5.13	4.94
Over 3	**AVG**	16.58	20.92	22.42	10.21	13.43	52.38	20.00	49.53	16.24	35.30	26.71
	STDEV	4.63	5.65	5.78	2.09	2.32	12.84	4.93	12.26	3.71	4.41	6.00
Over 4	**AVG**	15.58	21.63	20.44	11.48	13.79	50.24	21.49	76.18	16.58	30.40	29.14
	STDEV	4.57	6.23	6.26	3.81	1.84	12.97	8.54	4.89	4.63	3.29	5.83
Over 5	**AVG**	15.59	22.79	23.47	17.80	13.58	59.91	21.56	76.54	15.58	37.40	32.07
	STDEV	3.54	4.23	2.49	7.16	1.26	18.14	7.72	18.32	4.57	7.99	7.99
Over 6	**AVG**	16.48	18.47	23.62	18.64	12.36	56.83	21.67	56.07	15.59	35.02	28.69
	STDEV	3.17	2.54	1.60	7.59	1.20	12.70	4.81	9.03	3.54	9.61	5.85
Over 7	**AVG**	15.52	21.76	22.37	15.85	12.61	50.53	22.24	69.03	16.48	33.83	29.41
	STDEV	2.49	5.14	3.98	2.63	1.98	9.54	5.41	19.17	3.17	4.66	6.19
Over 8	**AVG**	16.38	21.61	22.55	12.07	10.63	46.53	23.17	51.20	15.52	35.04	26.48
	STDEV	21.67	7.30	1.10	3.04	2.77	7.01	2.84	18.27	2.49	2.79	5.29
Over 9	**AVG**	4.81	20.87	21.32	17.26	12.06	36.27	21.86	52.90	16.38	40.16	26.56
	STDEV	22.24	1.74	1.63	5.04	3.16	7.66	3.12	12.04	4.47	5.17	4.89
Over 10	**AVG**	5.41	21.15	22.45	15.53	13.49	47.06	18.67	47.73	12.22	43.68	26.89
	STDEV	23.17	3.25	2.73	2.98	3.48	11.44	3.26	9.44	2.67	5.64	4.99

Table 5 – Individual average head acceleration averages and standard deviations for each subject across 10 overs.

		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Subject 9	Subject 10	Average
Over 1	**AVG**	4.32	1.58	3.99	4.04	5.40	5.34	4.92	4.56	4.46	4.54	4.32
	STDEV	0.92	0.73	0.72	0.76	0.28	0.29	2.24	0.33	0.68	0.61	0.74
Over 2	**AVG**	4.31	1.80	4.01	3.90	5.26	5.46	5.99	4.32	4.63	5.17	4.50
	STDEV	0.24	0.42	0.29	0.80	0.36	0.45	1.66	0.92	0.92	0.44	0.69
Over 3	**AVG**	5.17	1.87	3.75	4.00	5.03	4.99	5.34	4.31	4.28	4.76	4.26
	STDEV	0.40	0.70	0.64	0.45	0.52	0.45	0.82	0.24	0.75	0.16	0.53
Over 4	**AVG**	4.89	2.10	4.92	3.92	4.79	5.17	4.68	4.23	4.23	4.87	4.32
	STDEV	0.36	0.59	1.77	0.45	0.53	0.40	1.28	0.37	0.73	0.29	0.71
Over 5	**AVG**	5.03	1.69	5.62	3.97	4.78	4.89	4.65	4.12	4.80	4.06	4.29
	STDEV	0.52	0.26	1.04	0.33	1.24	0.55	0.64	1.00	0.68	0.93	0.74
Over 6	**AVG**	4.79	2.02	4.58	3.27	4.55	5.09	5.83	4.52	5.12	5.06	4.45
	STDEV	0.53	0.28	0.56	0.18	0.35	0.19	0.38	0.65	0.76	0.44	0.42
Over 7	**AVG**	4.78	1.77	4.32	3.44	4.67	5.31	5.18	4.09	4.34	4.84	4.22
	STDEV	1.24	0.79	0.61	0.34	0.52	0.39	0.51	0.73	0.45	0.46	0.53
Over 8	**AVG**	4.55	2.09	4.12	3.69	4.84	4.75	5.91	4.56	4.66	5.03	4.40
	STDEV	0.35	0.14	0.47	0.35	0.43	0.51	1.63	0.80	0.46	0.55	0.59
Over 9	**AVG**	4.67	2.13	4.93	3.82	4.37	4.96	5.87	4.02	4.49	4.91	4.39
	STDEV	0.52	0.21	0.61	0.63	0.19	0.62	1.42	0.76	0.92	0.50	0.65
Over 10	**AVG**	4.84	1.88	4.86	3.49	4.77	5.04	4.72	4.49	4.58	4.87	4.30
	STDEV	0.43	0.30	0.75	0.27	0.30	0.58	0.51	0.53	1.37	0.33	0.55

Table 6 – Individual average SA acceleration averages and standard deviations for each subject across 10 overs.

		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Subject 9	Subject 10	Average
Over 1	**AVG**	65.63	90.52	81.07	71.95	64.55	87.28	71.24	89.39	62.29	84.31	78.06
	STDEV	15.50	4.42	5.93	6.49	5.92	2.71	11.96	7.65	4.88	2.18	5.79
Over 2	**AVG**	72.40	92.36	80.79	70.77	55.27	88.10	66.34	92.35	65.63	82.02	77.07
	STDEV	7.82	2.43	3.39	4.81	6.98	1.94	10.53	2.57	15.50	2.74	5.65
Over 3	**AVG**	72.46	90.87	82.49	59.69	61.29	89.95	72.20	90.82	72.40	86.29	78.45
	STDEV	10.25	3.12	4.44	7.27	9.83	2.78	6.74	2.31	7.82	2.06	5.15
Over 4	**AVG**	66.27	89.67	75.94	62.58	65.16	89.21	73.54	94.42	72.46	83.85	78.54
	STDEV	12.50	3.80	4.10	13.17	1.73	2.63	15.91	0.69	10.25	1.56	5.98
Over 5	**AVG**	65.72	92.32	76.08	74.81	64.52	91.16	76.52	94.13	66.27	88.55	80.49
	STDEV	8.42	2.02	3.40	9.32	9.52	3.03	7.71	2.59	12.50	3.63	5.97
Over 6	**AVG**	73.00	88.87	80.54	80.11	62.82	90.67	71.80	91.71	65.72	84.73	79.66
	STDEV	4.69	2.19	2.53	7.20	5.01	2.06	7.24	2.03	8.42	3.96	4.52
Over 7	**AVG**	68.97	91.52	80.54	77.60	61.99	89.17	75.01	93.72	73.00	85.41	80.88
	STDEV	7.68	4.56	1.36	5.33	8.52	2.26	8.62	2.04	4.69	2.68	4.45
Over 8	**AVG**	70.25	89.52	81.68	67.53	51.53	89.73	73.37	90.57	68.97	85.49	77.60
	STDEV	12.28	2.91	2.66	10.40	14.52	0.74	11.70	2.43	7.68	2.69	6.19
Over 9	**AVG**	76.79	89.75	76.81	76.79	61.52	85.86	72.95	92.25	70.25	87.67	79.32
	STDEV	6.26	1.39	2.92	6.26	10.59	3.10	6.27	1.47	12.28	1.30	5.06
Over 10	**AVG**	76.52	91.01	78.29	76.52	62.66	88.75	74.22	90.19	60.33	88.61	78.95
	STDEV	6.27	1.57	2.88	6.27	9.60	2.83	4.48	2.88	17.70	2.18	5.60

Table 7 – Individual average APV acceleration averages and standard deviations for each subject across 10 overs.

		Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8	Subject 9	Subject 10	Average
Over 1	**AVG**	5.32	1.63	3.64	3.27	5.52	5.43	5.34	5.42	4.75	3.84	4.74
	STDEV	0.03	0.06	0.01	0.01	0.01	0.00	0.26	0.04	0.02	0.01	0.05
Over 2	**AVG**	5.03	1.68	4.87	4.18	5.80	6.07	5.49	5.02	4.82	4.25	5.04
	STDEV	0.03	0.76	0.00	0.01	0.01	0.01	0.44	0.03	0.03	0.01	0.09
Over 3	**AVG**	5.49	1.99	5.63	5.57	5.16	5.84	5.81	5.96	4.69	3.96	5.24
	STDEV	0.44	0.51	0.01	0.01	0.02	0.01	0.65	0.01	0.02	0.00	0.11
Over 4	**AVG**	5.81	3.11	4.66	4.16	5.72	5.35	5.72	6.13	4.80	4.19	5.12
	STDEV	0.65	0.53	0.02	0.02	0.01	0.00	0.53	0.03	0.02	0.00	0.05
Over 5	**AVG**	5.72	3.04	6.52	6.46	6.18	6.26	5.45	6.14	4.53	3.99	5.55
	STDEV	0.53	0.32	0.02	0.01	0.03	0.01	0.32	0.01	0.02	0.01	0.06
Over 6	**AVG**	5.45	2.05	6.05	6.56	6.62	6.40	5.54	5.90	4.62	4.88	5.74
	STDEV	0.32	0.65	0.01	0.00	0.01	0.00	0.29	0.01	0.02	0.01	0.06
Over 7	**AVG**	5.54	3.46	5.02	5.95	6.76	6.52	5.76	5.71	4.56	3.96	5.57
	STDEV	0.29	0.30	0.01	0.01	0.02	0.01	0.37	0.01	0.01	0.01	0.06
Over 8	**AVG**	5.76	3.06	3.57	6.63	6.64	5.55	5.66	5.36	4.46	4.02	5.41
	STDEV	0.37	0.28	0.01	0.01	0.04	0.01	0.53	0.05	0.01	0.01	0.10
Over 9	**AVG**	5.55	2.12	3.99	5.94	5.47	5.96	5.47	5.00	3.86	4.34	5.09
	STDEV	0.01	0.55	0.01	0.01	0.01	0.01	0.39	0.03	0.03	0.01	0.08
Over 10	**AVG**	5.96	1.71	0.06	0.05	0.08	0.06	5.30	0.06	0.09	0.06	0.81
	STDEV	0.01	0.25	0.01	0.01	0.01	0.01	0.38	0.01	0.06	0.00	0.07

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